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STEEL TREATING PRACTICE

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STEEL TREATING PRACTICE

BY

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PREFACE

Steel treating was once an art mysterious enough to be ranked with the black arts. In early legends those who dealt with iron and steel are often pictured as deformed beings, usually dwellers underground. Sometimes a normal human being, more frequently a hero, performed some feat in the art but only by the aid of magic or superhuman power. The connection between darkness and steel treating has only recently been broken. Scientific knowledge has removed the magic and the darkness, and steel treating is carried on by ordinary men. To the uniniated, however, the element of mystery seems still to remain. He finds that scientific rules sometimes fail and that theory and practice are often at variance. Unfortunately the literature of steel treating has put far more stress upon theory than upon practice, rarely connecting the two, and has sometimes opposed methods that eventually proved to be correct. Much has been said about exact methods and specifications and little about the variations that can be permitted. Dollars and cents find but little place in discussion although looming large in practice.

To the worker in other fields a practice that seems to vary so widely and that also seems to neglect the dollar sign, is hard to understand. When he seeks information he finds on the one hand charts that purport to give briefly full information about the art. On the other hand he finds practice apparently regulated by innumerable, minute details. The result is confusing.

This book, therefore, will attempt to outline the requirements of practice rather than to discuss the theory of steel treating. Practice, however, depends upon technical principles and must therefore be discussed in the light of these principles. The basis of steel treating is comparatively simple and can be easily understood if not buried in detail and technical terms. This outline will therefore present only the simple basic principles as they are connected with practice and will include not only standard methods, but also variations that are important in industry and behind which the dollar sign stands prominently.

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This item of cost will find a place but will not be considered in detail because of the variable conditions that exist. The text has been written not for the technician, but rather for those who desire a general view of the field covered in steel treating practice.

Such discussion needs more angles than one, and the author wishes to express his appreciation to Mr. R. B. Schenck of the Buick Motors Co., Mr. H. F. Wood of the Ingalls-Shepard Division of the Wyman-Gordon Co., Mr. H. M. Spears of the Chevrolet Motor Co., Mr. H. M. Schmid of the Central Alloy Steel Corp., Mr. H. M. Bray of the Colonial Steel Co., Mr. E. J. Janitzky of the Illinois Steel Co., Mr. H. P. Tiemann of the Carnegie Steel Co., Mr. R. S. MacPherran of the Allis-Chalmers Co., and other friends who have supplied material and information or who have read and criticised parts of the manuscript.

R. H. S.

Los Angeles, California
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STEEL-TREATING PRACTICE

INTRODUCTION

The heat treatment of steel began with a few comparatively simple processes applied on a small scale to tools and weapons, processes that can be divided into two general classes—those for softening and those for hardening. Heat treating was but a small part of the blacksmith's art, and skill with the hammer had, perhaps, a greater value than skill in hardening. A fine grain in steel was obtained by forging rather than by heat treating, a practice that is by no means obsolete. The blacksmith's forge was the first heat-treating furnace, and temperature was determined by heating colors rather than by degrees in some scale of temperature. Only one kind of steel was available, this corresponding approximately to the present-day carbon tool steel and made by heating wrought iron in contact with solid carbonaceous material, for example charcoal.

In contrast, heat treating has now become a major operation carried on on a large scale for quantity production and by precise methods that have replaced the rule-of-thumb practice and secrecy of a former day. The blacksmith's forge has been replaced by heat-treating furnaces designed for production and so equipped that little or no skill is required of the operator. The products treated are of many kinds, and the steels available are of many types and kinds in place of one. Twenty-five or thirty years ago, the details of steel-treating practice could have been well covered in a book of moderate size and, to a considerable extent, in the light of contemporary knowledge of the principles involved. Today, however, the subject is too vast for any brief discussion. What was once only a detail in practice is now a subject in itself. In this volume, therefore, no attempt will be made to give in detail a complete description of methods, materials, and equipment, but rather to present a

general picture of the elements and principles of general practice. Individual methods differ because of difference in requirements, and, as a result, marked difference of opinion with regard to processes will be found, but such difference is usually one of method rather than of the principles involved. Occasionally, however, the principle involved may be at isssue.

Differences in opinion that concern the principle involved are often due to lack of complete information. Technical training with regard to steel has frequently been one-sided and incomplete. The introduction of the microscope opened up a new field, an extensive field, in which steel could be studied by itself and without direct connection with practice. Scientific investigation showed the reason for certain practice and, also, that other practices had no reason for existence. But, as in almost all early investigation, condemnation went too far because based upon incomplete information. For a time, the microscope ruled supreme. But continued investigation from other angles proved that microscope could tell only a part of the story. Unfortunately, technical training leaned too far in that direction, and many a beginner was completely lost when faced with problems for which the microscope has no answer. As a result, "Microscopical examination reveals no defects in the material" was a common reply to questions regarding many problems.

The principles of heat treating may be considered as a science in itself, but in the application of such principles in the manufacture of a product that must stand up in service, other principles are also involved. Design, method, cost, and other factors enter into heat treating for service and must, therefore, be taken into account. Too often have material and heat treatment served as alibis for trouble from sources outside either field. No knowledge of heat treating for service can be complete without a knowledge of the other factors that can enter.

To a recognition of the factors that enter into steel-treating practice should be added a recognition of the constant change in such practice. New processes, new methods, and new equipment are introduced almost every day; some that are described in the text were unknown when this book was started. Not all of these new developments have been included, because some have not yet found their way into general practice. To keep up with the progress in practice requires continued reference

to engineering and trade journals and to manufacturers' catalogues. The constant change limits the material available in describing steel-treating practice but does not prevent the description of methods and equipment now more or less obsolete, because practice must be described historically to some extent and because practice that is obsolete under one set of conditions may be the best under another set.

The development of modern steel-treating practice has been accompanied by an increase in the number of recognized processes and operations but, unfortunately, there has not been a parallel development of descriptive terms for such processes, and only a few have been thus recognized. With but one type of steel and only two general objects—softening and hardening—the steel treater was once content with a few terms that have continued to the present time. But practice now recognizes several processes where he saw but one. For some of these newly recognized processes, terms have been invented, but others have no name, either because of a lack of words suitable for description or because past practice has included them under some general and convenient term. Processes and operations, furthermore, often overlap to such an extent that the application of separate terms is somewhat difficult.

An effort has been made to name various processes and operations and to formulate a set of definitions, and a set of such definitions has been sponsored by several engineering societies in cooperation. The effort has been to define operations rather than objects, but, unfortunately, processes can sometimes be described only by the results obtained. Some of the terms applied to steel treating have been in service so long that it is difficult to obtain any general acceptance of a meaning that is out of line with long-established usage. Again, a general term may have different meanings to different individuals because of differences in requirements that may demand, perhaps, only a slight modification of the practice described under a given term. The initiated may understand the differences, but to the uninitiated the result is confusing.

However valuable such definitions may be to the initiated, they are not entirely serviceable in describing heat-treating processes. In the literature of steel treating, these terms have been employed long before distinct definition was attempted but with a definite meaning that is often missing from a brief

definition. Definition or description must take such long usuage into account, particularly if it is still continued. Again, processes may require a detailed description because of the many factors that enter. Heat-treating processes are, therefore, better described than defined. The proposed definitions have been included in the Appendix because convenient for reference. In the text, the processes commonly including the various terms will be briefly described so that the reader will understand the meaning of the terms when used, but such description is not to be considered as definition. Such brief description will be followed by detailed discussion of operations and processes in individual chapters.

CHAPTER I

THE BASIC PRINCIPLES AND PRIMARY PROCESSES OF STEEL TREATING

The Object of Heat Treating Steel.—"Steel" is a general term that now includes a large and constantly increasing number of alloys, of various compositions, all basically alloys of iron and carbon. As cast, rolled, or otherwise formed while hot, steel has many desirable properties and is useful in many ways, but its utility is greatly increased by other desirable properties that can be obtained by processes of heating and cooling in the solid state. Within limits that will be described, the same steel can be made hard and brittle by one process of heating and cooling, and, by comparison, at least, soft and ductile by another. These processes of heating and cooling in the solid state by which the properties and condition of steel can be changed are classified by the term "heat treatment."

Critical Temperatures.—The principal processes of heat treatment depend upon changes in internal structure that occur at definite temperatures, known as "critical" or "transformation" points, when solid steel is heated or cooled past those temperatures. If all processes are not so directly dependent, they will be more or less restricted by these temperatures and the changes in structure that they represent. Steel treating was once carried on more or less blindly but now approaches an exact science built upon the foundation supplied by these critical changes. The hardener of a former day recognized them vaguely and knew that certain heating colors were required. His modern successor knows the exact changes that take place and the exact temperatures at which they occur, necessarily, and bases discussion upon them. Critical changes, however, do not belong to technical practice alone but are common in every-day experience. For example, the boiling of water at 212° F. (100° C.) and the freezing of water to ice at 32° F. (0° C.) are critical changes at critical temperatures known, respectively, as the boiling and freezing points of water.

Cooling and Heating Curves of Water.—Such a change can be pictured by a simple diagram, for example Fig. 1 (*a*), the cooling curve of pure water. By means of a freezing mixture or in other ways, water can be cooled to freezing, and the rate of cooling observed by means of a thermometer and a watch. The results are recorded in a diagram, such as that of Fig. 1 (*a*) in which time is marked off along the horizontal line and temperature along the vertical line. The rate of cooling can be plotted on this diagram by a curve such as that of Fig. 1 (*a*). Observation shows a gradual fall in temperature until the water has cooled to 32° F. (0° C.), indicated by the oblique line. At 32° F. (0° C.) cooling stops for some time, as indicated by the horizontal line of the curve, and then continues, as indicated by the curve. Observation

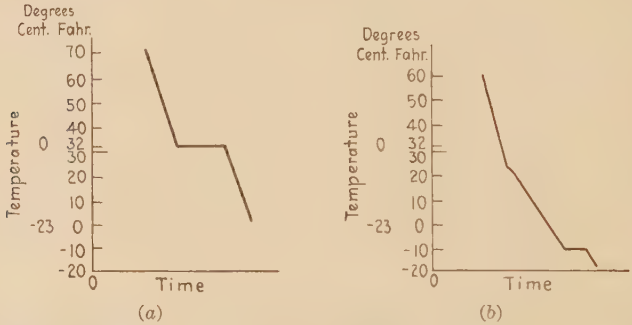


Fig. 1.—(*a*) Freezing point curve, pure water, (*b*) cooling curve 5 per cent salt solution in water.

shows that ice begins to form at 32° F. and continues to form until all the water is frozen, and that cooling begins again as soon as freezing is complete. The reverse process, heating from below the freezing point, can be pictured in the same way, showing by a similar horizontal line the melting point at 32° F. (0° C.). Similar curves will be obtained with other pure substances: for example salt, lead, tin, and other compounds and metals.

Cooling and Heating Curves of Salt and Water Solutions.—In a similar way the heating and cooling of a mixture of two substances can be observed, and similar heating and cooling curves drawn, but as such mixtures can be made in all proportions, from 100 per cent of one to 100 per cent of the other, a series of curves will be necessary to cover the entire range. To illustrate the effect of heating and cooling such mixtures, com-

binations of salt and water are perhaps most suitable because of their widespread occurrence and use and because the results are similar to those obtained by heating and cooling solid steel. The observation of the cooling of solutions of salt and water brings out the familiar fact that the addition of salt lowers the freezing point. The cooling curves of a 5 per cent solution of salt in water (Fig. 1 *b*) shows that such a solution cools below 32° F. (0° C.) without freezing and at a regular rate until the temperature has fallen to 23° F. (−5° C.). Observation shows that ice begins to separate at this temperature and continues to separate as cooling continues. The temperature does not remain constant as ice separates, as on freezing water, but continues to fall although at a slower rate, as indicated by the

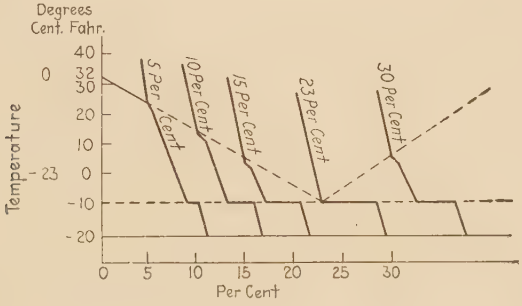


FIG. 2.—Cooling curves—salt solutions.

change of direction of the curve. At −10° F. (−22½° C.) cooling ceases until the solution has completely frozen and then continues, as indicated by the horizontal line of the curve and the oblique line below.

As shown by the curve of Fig. 2, the cooling curves of salt solutions containing less or more than 23 per cent of salt are similar to the curve for the 5 per cent solution, but with increasing salt up to 23 per cent, the temperature at which ice begins to separate is progressively lowered. Solutions containing less or more than 23 per cent of salt have two change points indicated on their curves. For solutions containing less than 23 per cent of salt, the upper point indicates the temperature at which ice begins to separate. For solutions containing more than 23 per cent of salt there is a similar separation from solution but of salt, not ice, and the temperature at which such separation starts is progressively higher as the salt content is increased.

Behavior of Salt and Water Solutions on Freezing or Melting.—The 23 per cent solution is distinctive in having but one change point, that at −10° F. (−22½° C.). When this solution is cooled, no ice separates and no change in the rate of cooling occurs until the temperature reaches that point. Here freezing begins, as shown by observation, and continues without change of temperature, this being indicated by the horizontal line of the curve—a curve that closely resembles that obtained with pure water. The freezing point of the 23 per cent solution is also the point of final freezing of all salt and water solutions.

The common temperature of final freezing at −10° F. (−22½° C.) is due to the eventual formation of a solution containing 23 per cent of salt during cooling of any salt solution to solidification. Solutions that contain, at the start of cooling, less than 23 per cent of salt gradually become richer in salt as ice separates on cooling. Likewise solutions that at the start contain more than 23 per cent of salt gradually lose salt from solution as cooling continues. Eventually, just 23 per cent of salt will remain in solution, and final freezing will take place without a change of temperature, as already described. The change in composition with falling temperature.can be determined by chemical analysis.

Eutectic Mixture.—The behavior of the 23 per cent solution is the key to the behavior of all salt solutions on freezing. An examination of a frozen 23 per cent solution shows that the solid mass is a mechanical mixture composed of salt and ice in alternate layers. This structure is probably due to the persistence of the 23 per cent solution. If, on freezing, ice first separates, the solution remaining must contain more than 23 per cent of salt, and, therefore, some salt must separate to balance, this process continuing until freezing is complete. Liquid solutions that freeze in this way are known as "eutectic" solutions, the solid mass, composed of alternate layers of the two constituents, as the eutectic or eutectic mixture, being the mixture with the lowest melting and freezing point.

Structure of Frozen Mixtures of Salt and Ice.—Because of the separation of ice, the solid mass formed by the freezing of solutions containing less than 23 per cent of salt will be composed of free ice mixed with islands of the eutectic. The more salt in the original solution, the greater will be the amount of eutectic in the frozen mass. The proportion can be determined mathematically. For example, the freezing of a solution that con-

tained originally 11.5 per cent of salt will result in a solid mass containing ice and eutectic mixture in equal amount. Similarly, estimates can be made for solutions containing more than 23 per cent of salt to determine the ratio between free salt and eutectic.

Critical-point Diagram of Water-salt System.—In the diagram of Fig. 2, the cooling curves are arranged in order, and corre-

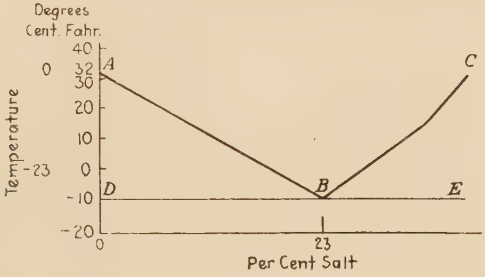


FIG. 3.—Critical point diagram, salt and water.

sponding points have been connected by line, forming a diagram that is illustrated by Fig. 3, the critical-temperature diagram of solutions of salt and water, a V curve. In this diagram, temperatures are represented along the vertical line as before, but composition, not temperatures, is represented by points along the horizontal line. In this diagram, line *DBE*, at −10° F.

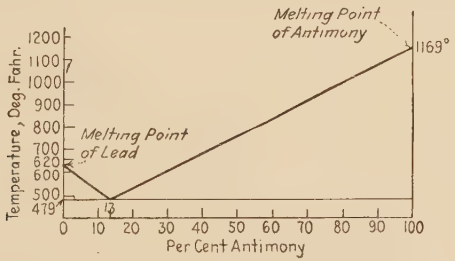


FIG. 4.—Melting and freezing point curve, lead-antimony alloys.

(−22½° C.), indicates the temperature of final freezing and of the start of melting for all solutions, the freezing and melting point of the eutectic. Lines *AB* and *BC* indicate the temperature at which any solution begins to freeze or finally melts and also the change in composition, due to the separation of ice or of salt, as freezing continues, or the reverse on melting.

Eutectic Mixture in Alloys.—Other solutions and alloys behave in the same way on melting or freezing and have, there-

fore, similar critical temperature diagrams, for example, the alloys of lead and antimony. The critical temperature diagram of these alloys (Fig. 4) closely resembles that of water and salt (Fig. 3). Description of the process of freezing or of melting will be practically the same. The eutectic of lead-antimony alloys contains 87 per cent of lead and 13 per cent of antimony and solidifies in alternate layers of each constituent. Below the point of final freezing this mechanical mixture is formed. Above the temperatures represented by the arms of the V, a liquid solution exists.

Critical Temperatures in the Solid State.—The transformations discussed have all been changes in state, from liquid to solid or the reverse, freezing and melting. The critical temperatures are freezing and melting points. Many such substances, and mixtures, including those just discussed, have no critical points other than those connected with freezing and melting. Some substances and mixtures, however, have critical points that represent changes in structure or physical condition without a change in state. Sulphur, for example, will change from the crystalline to the amorphous form when held at temperatures somewhat below the melting point. Other substances when heated and cooled go through such changes, often without any visible indication. Such transformation, however, will be indicated in the heating and cooling curves. Pure iron and also the alloys of iron and carbon, which are the basis of steel, undergo changes in structure and physical properties when heated and cooled in the solid state, changes that can be indicated in a diagram.

Iron-carbon Alloys.—The critical temperature diagram of the iron-carbon alloys is complicated by the existence of two forms in which carbon can be present; carbon in the form of graphite, and carbon chemically combined with iron in a compound known as "carbide of iron," which contains 6.67 per cent of carbon (Fe_3C). Carbide of iron is very hard and increases the hardness of steel in proportion to the amount present. Both graphite and carbide of iron are important in the manufacture of cast iron, but graphite does not enter into steel, and the two constituents of steel are, therefore, iron and carbide of iron. Commercial steels contain other substances that may mix with iron or carbide of iron so that they are no longer pure. For this reason other terms are now used, and iron is replaced by *ferrite;* carbide of iron by *cementite.* In general usage, however,

the word "carbon" is preferred to "cementite" because of long usage and because analysis estimates the amount of carbon, not cementite, present. The series of alloys of iron and carbon, or iron and iron carbide, that are the basis of steel contain up to about 1.50 per cent of carbon. The behavior of the members of this series in the solid state resembles the behavior of corresponding members of the series of solutions of salt and water when the process of heating and cooling are observed, although the changes in the alloys of iron and carbon take place in the solid state. The diagrams drawn by observation of the critical temperatures are therefore much alike.

Heating and Cooling Curves of Pure Iron in the Solid State.— Pure iron may be considered as the starting point of the series of iron-carbon alloys just as pure water was considered as the starting point of the series of water-salt solutions. The heating and cooling curves for pure iron in the solid state (Fig. 5 (*a*) and (*b*)) show two "breaks" that indicate changes in internal structure without a change in state from solid to liquid, or the reverse. These changes take place without any visible indication, but they do represent changes in physical condition. At the upper point of the heating curve, pure iron will recrystallize, and at the lower point it loses its magnetism. The upper point may be considered as corresponding to the freezing or melting point of water, but the lower point has no parallel in water and, because it has little effect on heat treatment, will be neglected here to avoid confusion. The transformations that occur on heating pure iron are reversed on cooling, but at different temperatures. The critical temperature points are higher on heating than on cooling, so that two distinct curves are obtained.

Heating and Cooling Curves of Pure Alloys of Iron and Carbon. The addition of carbon to iron has the same effect upon the critical points as the addition of salt to water, the upper critical point being lowered as the carbon content increases, just as the addition of salt to water lowers the point at which freezing begins. Likewise, the introduction of carbon brings in a second critical point, at lower temperature, corresponding to the melting and freezing point of salt solutions, at $-10°$ F. ($-22\frac{1}{2}°$ C.). These points are indicated on the heating curve (Fig. 6 (*a*)), at *Ac*3 and *Ac*1, respectively, and on the cooling curve (Fig. 6 (*b*)), in corresponding positions at *Ar*3–2 and *Ar*1. It is evident from a study of the curves that these transformations do not occur at

one definite temperature, like the freezing and melting point of water, 32° F. (0° C.), but cover a small range of temperature, starting at one point and ending at another, as indicated at $Ac1$ and $Ar1$. This fact is sometimes overlooked in designating temperatures for heat treatment but is of importance because the transformation must be complete. The temperature at which the change ends can be considered as a critical point.

Symbols Representing Critical Temperature Points.—The numbers and letters that mark the various critical points indicated in the diagram are used in accordance with a definite system. The letter A is used to indicate all transformation points. The addition of the letter c distinguishes the critical points of heating from the corresponding critical points of cooling,

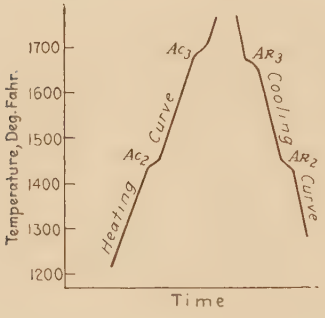


Fig. 5.

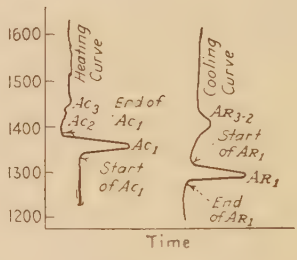


Fig. 6.

Fig. 5.—Pure iron, (*a*) heating curve, (*b*) cooling curve.
Fig. 6.—0.40 per cent carbon steel, (*a*) heating curve, (*b*) cooling curve.

which are denoted by adding the letter r, c and r being the initial letters of French words that mean, respectively, heating and cooling. The three critical points that occur on both heating and cooling are numbered 1, 2, 3, from the lowest to the highest. As the carbon content increases, these points come together, and the numbers will therefore be combined, as at A_r3–2 on the curve of Fig. 6 (*b*). If reference is made to a particular critical point without regard to heating or cooling, the letter c, or r, is omitted. For example in Fig. 6 (*b*), the A_{c1} and A_{r1} points are the A_1 points of 0.40 carbon steel. Similarly A_2, A_2, A_{3-2} would denote corresponding critical points for both heating and cooling.

Critical-temperature Diagram of Iron-carbon Alloys.—Similar cooling curves can be obtained with other members of the

series of iron-carbon alloys that are the basis of steel, and in Fig. 7 (*a*) curves of a number of these alloys have been arranged in order according to carbon content. By drawing lines through corresponding points, the dotted lines, a critical temperature diagram is formed, shown by itself in Fig. 7 (*b*). In this diagram temperature intervals are still marked on the vertical line,

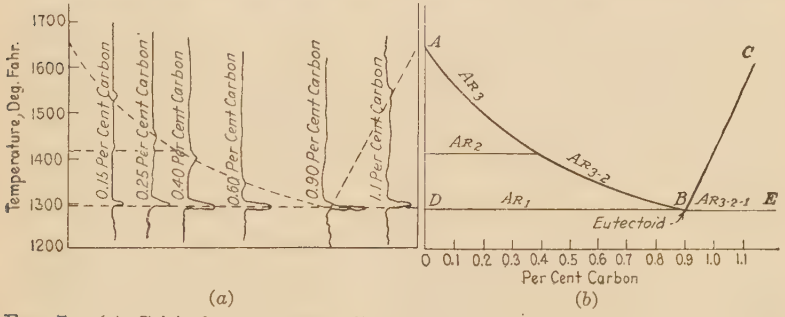


FIG. 7.—(*a*) Critical temperature diagram, (*b*) solid alloys of iron and carbon from cooling curves.

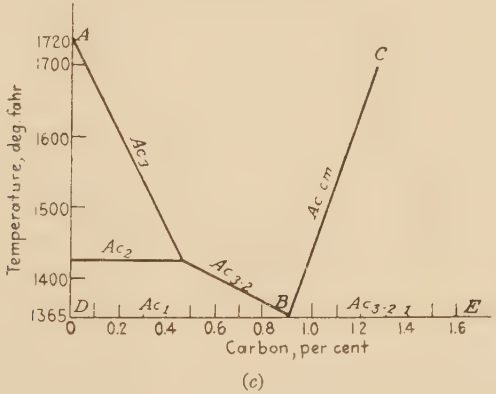


FIG. 7 (*Continued*).—(*c*) Critical temperature diagram of solid alloys of iron and carbon based on heating curves.

but composition is represented along the horizontal line instead of time. This diagram is like the corresponding diagram of the water-salt series (Fig. 3), obtained in the same way, and, therefore, represents somewhat similar conditions. Just as increasing salt, up to 23 per cent, lowers the temperature at which freezing begins, so does increasing carbon lower the temperature at which recrystallization takes place. The cooling curve for the alloy containing approximately 0.90 per cent of carbon is similar

to the cooling curve for the 23 per cent salt solution and the upper critical point occurs at increasingly higher temperature as the carbon content increases above 0.90 per cent, just as increasing salt above 23 per cent raises the temperature at which freezing begins.

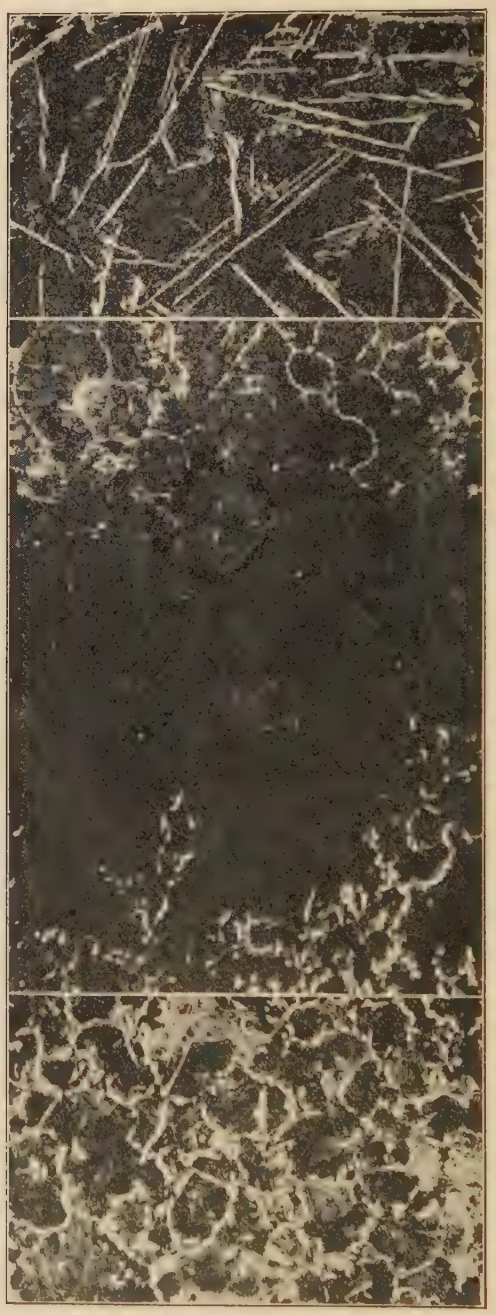
Normal Structure of Iron-carbon Alloys. Pearlite.—The parallel continues when the structures obtained by cooling are examined. Like the frozen 23 per cent salt solution, the alloy containing 0.90 per cent of carbon, when cooled below the temperature represented by the line *DBE* (Fig. 7 (*b*)), is composed of a mechanical mixture, and this mixture is composed of iron and carbide of iron in alternate layers. This alloy is termed "eutectoid," meaning "like eutectic," the term "eutectic" being reserved for liquid solutions. Alloys containing less than 0.90 per cent carbon separate out pure iron on cooling to temperatures represented by the line *AB*, paralleling the separation of ice from salt solutions: similarly, carbide of iron separates from iron-carbon alloys containing more than 0.90 per cent of carbon on cooling to temperatures represented by the line *CB*, corresponding to the separation of salt on cooling solutions containing more than 23 per cent. Alloys of iron and carbon containing less than 0.90 per cent of carbon, cooled comparatively slowly to temperatures below that represented by line *DBE*, will be composed of "islands" of the eutectoid mixed with free iron, or *ferrite*. If the carbon content is more than 0.90 per cent, similar cooling will produce a mechanical mixture composed of islands of eutectoid mixed with free carbide of iron, *cementite*.

The structures described are illustrated in Fig. 8*A*, magnified to 100 diameters. This magnification is too low to show the alternate layers, but these can be seen in the photographs of Fig. 8*B*, of higher magnification. The mechanical mixture formed by cooling the eutectoid alloy, illustrated in the photograph of 0.80 carbon steel in Fig. 8*B*, is called "pearlite" because of the appearance when etched, or lamellar pearlite to indicate the layers. The series of Fig. 8*A* illustrates the effect of increasing carbon, the black islands being pearlite. In the alloys containing less than 0.90 carbon, excess iron separates, showing white in the photographs. Excess carbide of iron, separated on cooling alloys containing more than 0.90 per cent carbon, is also white, but can usually be distinguished by standing out in relief and by being unmarked, in contrast to the much softer

(1) (2) (3)

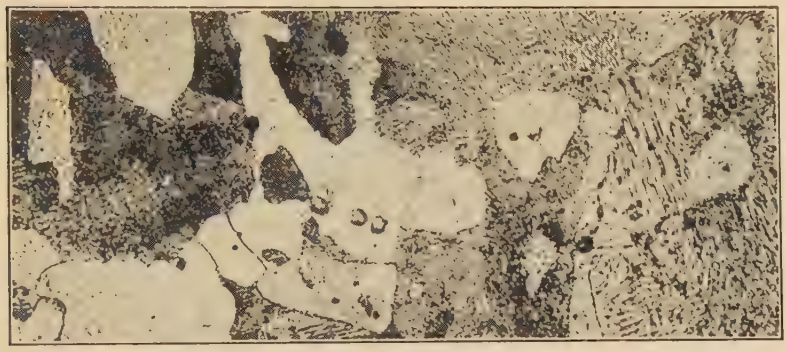
(4) (5) (6)

FIG. 8A.—Showing structure with increasing carbon. (1) Carbon 0.05 per cent, (2) Carbon 0.10 per cent, (3) carbon 0.18 per cent, (4) carbon 0.24 per cent, (5) carbon 0.30 per cent, (6) carbon 0.48 per cent.

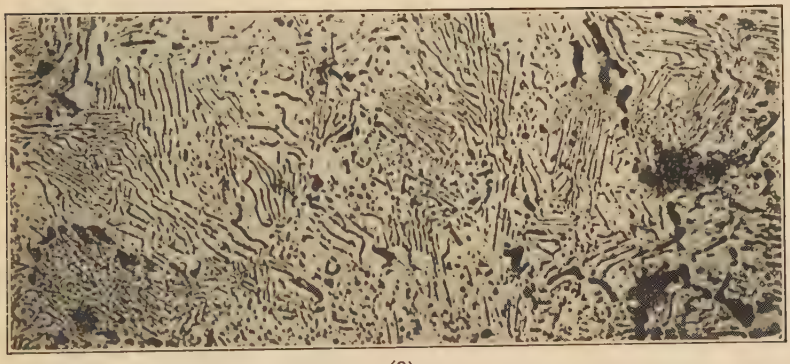


(7) (8) (9)

FIG. 8.4 (*Continued*).—Showing structure with increasing carbon. (7) Carbon 0.55 per cent, (8) shows carbon 0.70 per cent at left side, pearlite in the center and carbon 1.10 per cent at right, (9) carbon 1.50 per cent.



(1)



(2)

(3)

FIG. 8*B*.—500 diameters. (1) Carbon 0.50 per cent, (2) carbon 0.80 per cent lamellar pearlite, (3) carbon 1.20 per cent.

iron. The more highly magnified photographs of Fig. 8*B* show the structures more clearly. In C the cementite is black.

The amount of pearlite present indicates approximately the carbon content; 100 per cent pearlite will be presumed to be present when the carbon content is 0.90 per cent, although this will vary, as will be described. Steel containing 0.45 per cent carbon will therefore be composed of pearlite and free iron in equal quantities (0.45/0.90 = ½). Similarly, a 0.20 carbon steel will contain 0.20/0.90 pearlite or 2/9; 0.30 carbon steel 0.30/0.90 or ⅓, as shown in the photographs.

Solid Solutions.—The parallel between solutions of salt and water and alloys of iron and carbon continues when the results of the heating are considered. Frozen mixtures of ice and salt begin to melt when heated to −10° F. (−22.5° C.), first forming a 23 per cent solution at that temperature by the melting of the eutectic mixture of ice and salt. The temperature remains constant until melting of the mechanical mixture is completed. A rise in temperature then begins and continues and, as this goes on, the free ice or free salt gradually enters the solution until all has dissolved, composition and temperature following along line *BA* or *BC* (Fig. 3). In this diagram, temperature and composition are represented by a point. If this point lies within the arms of the V, solution is complete. The iron-carbon alloys form solutions when heated to a temperature above the line *ABC* of Fig. 7, but without melting. These solutions are formed in the solid state, and are known as "solid solutions"—structures just as homogeneous as liquid solutions.

Many alloys form solutions in the solid state. Some form such solutions for all compositions, for example, silver and gold. Others form a series of solid solutions each of which covers a definite range of composition, for example, copper and zinc. Still others form a solid solution in but one range of composition, this class including the alloys of iron and carbon. The location of the solid solution in the iron-carbon series is shown in the complete critical temperature diagram in the Appendix. The maximum amount of carbon that can be held in solution is 1.7 per cent, a dividing line between steel and cast iron. The iron-carbon diagram will not be discussed here because only a part is important in steel treating. The term "carbon" is used for convenience, but the two constituents are iron and carbide of iron—a compound having the chemical formula Fe_3C and com-

posed of approximately 93.4 per cent of iron and 6.6 per cent of carbon.

Fixing the Solid Solution.—The majority of processes for heat treating steel depend upon the formation of a solid solution by heating to temperatures above the A_{c3} point, this being accompanied by recrystallization, unless certain conditions to be described prevent. If such heating is followed by relatively slow cooling to a temperature below the A_{r1} point, the mechanical mixture pearlite is formed, although this may be suppressed by alloying elements. Relatively slow cooling is necessary because the transformation requires time; the freezing of water at 32° F. (0° C.) is not instantaneous, nor is the final freezing of salt solutions. Now, if cooling from the A_{c3} point is relatively rapid, the change to pearlite will be prevented, and structures that exist only at temperatures above the upper critical point will, therefore, be "fixed" by rapid cooling and, theoretically, would remain when cooling ends. As a matter of fact, however, rapid cooling does not fix a single, definite structure; the change from solid solution to mechanical mixture passes through several stages any one of which may be the final result, this depending upon the conditions and rate of cooling and upon the composition of the steel.

The Critical Temperature Diagram as a Guide in Steel Treating.—The critical-point diagram is important in steel treating because it shows the exact temperature at which the transformations take place and is, therefore, a necessary guide. For complete information, two diagrams are required, one for heating, the other for cooling, because of the difference in the position of the corresponding transformation points. Diagrams intended for use in heat treating steel were originally based upon the cooling curves. Such diagrams have some place in practice because some processes are based upon them. The principal processes of steel treating, however, are based upon the transformations of heating and require that the change be complete, that the temperature of heating be above A_{c3}, not A_{r3}. Working diagrams are, therefore, based upon the heating curves.

Presuming the critical point diagram of Fig. 7 (*c*) to be drawn from heating curves, line *DBE* represents the temperature at which the mechanical mixture pearlite goes into solid solution, the A_{c1} point. Lines *AB* and *BE* represent the A_{c3} point for

all alloys of iron and carbon, the temperatures required for hardening and refining operations. The A_{c3} point gradually approaches the A_{c1} point until the two are identical. Line AB represents temperatures at which solution is complete for alloys containing less carbon than pearlite—hypoeutectoid they are called. Line BC represents the temperatures at which alloys containing more carbon than pearlite, hypereutectoid, are in complete solution. For the first, line AB represents the hardening and refining temperatures, but BE, the hardening and refining temperature for the other and not BC, the line for complete solution, which is designated A_{ccm} (the symbol for the upper critical point of hypereutectoid steels). 1.5 per cent carbon is the maximum content for steel and represents a comparatively small amount of excess cementite, at least in comparison with excess ferrite in the hypoeutectoid alloys. Cementite is harder than hardened steel so that complete solution has no advantage in hardening. Furthermore, any advantage that complete solution might offer would be more than offset by the increase in grain size resulting from heating so far above the A_{c3} point. Steels containing carbon in the range between the pearlite point and the upper limit are all hardened or refined within the same working range of temperature.

Critical Temperature Range.—The range of temperature between the A_1 and A_3 points is known as the critical temperature range, and, for the iron-carbon alloys, is bounded by the line DBE and the line ABC. The term "critical temperature range," often shortened to "critical range," is sometimes used rather vaguely, in textbooks and technical articles, as applied to steel, for which the existence of two sets of critical temperatures is perhaps responsible. In a broad sense the critical range lies between the A_{r1} and the A_{c3} point, the lowest and highest temperatures at which transformation takes place. But in the sense ordinarily employed the term refers to the range of temperature between the A_{c1} and A_{c3} points, temperatures that mark the transformations of *heating*. But when these points come together, as at the pearlite point, the term "critical range" refers to the range of temperature between A_{c1} and A_{r1}, as no other is possible. This usage will be employed in the text unless otherwise stated. Some reference to the critical range of *cooling* will be required, this range lying between the A_{r3} and A_{r1}

points. The range of temperature between the A_{cm} and A_{3-2-1} points is also a critical range, A_{cm} marking the separation or final solution of cementite. For reasons already explained, this critical range is not of particular importance in steel treating although reference to the A_{cm} point will be necessary.

The Critical Range as a "Point of Reference."—The critical temperatures are convenient points of reference in describing or distinguishing steel treating processes. All these temperatures are included in the term "critical range," and to this range heat treating processes can be referred. Some processes depend directly upon heating to temperatures above or within the critical range; some do not. The temperature employed in any process may be limited, however, by the critical range. Processes that require heating to temperatures below the critical range are thus definitely limited. Processes that are not dependent upon the critical transformations may employ a range of temperature that can extend considerably above the critical range, but the upper limit will usually be restricted by the increase in grain size that results from such overheating, determined by the number of degrees of temperature above the critical range.

Steel-treating Terms.—Although the critical temperatures are now definite guides in practice, steel treating was once carried on without any knowledge of their existence, although the necessity of heating to a definite point was obvious. The results of treatment were apparent, although nothing was known about structures. The steel treater knew that by one method steel was hardened, by another, softened, and that by still other methods a degree of hardness between the extremes could be obtained. The processes by which these different results were produced were named, respectively, hardening, annealing, and tempering. Refining of the grain structure on hardening or annealing was also recognized but more as a part of these processes than as a separate process. Refining naturally accompanies hardening and annealing when a temperature above the critical range is employed. The steel treater also knew that hardening required rapid cooling; annealing, slow cooling. Upon the facts that he knew were based the common terms of practice, and usually upon the result. The slow cooling of annealing, however was recognized, for anneal means "to bake." Limited knowledge needed few terms, but occasionally supplementary terms were introduced to describe some variation in practice.

Of these, a few have survived because applicable in some particular field, but the greater number have become obsolete. These have disappeared because the processes represented have been proved to be unnecessary or to be only a slight modification of methods in common use. The discovery of processes was not difficult when knowledge was limited.

For newly recognized processes, scientific investigation, not accident nor guesswork, is responsible. Modern practice recognizes two or, perhaps, more processes where only one was once known. Processes apparently alike in method and even in result have been shown to be distinct because of differences in the structures obtained. For some of these newly recognized processes new terms have been devised. On the other hand, some processes, often of long standing, have no generally accepted names although well recognized. Terms, however, are not always necessary, because the operations required can be specified clearly—a better practice than using terms that may be more or less indefinite.

Basic Processes of Steel Treating in Brief.—So many conditions must be covered in describing steel-treating processes that definition or even brief description may be difficult. Definitions that have been proposed are not intended for purposes of description. The examples mentioned in the introduction and given in the Appendix are, however, convenient for reference. Steel-treating processes require detailed description, which will be reserved for later discussion. But it will now be necessary to use these terms in the text and the processes to which they refer will, therefore, be described briefly. These descriptions are based upon the commonly accepted meaning of the terms, avoiding the exceptions, and are not to be considered as definitions.

The direct processes of heat treating, hardening and annealing, may be distinguished by the difference in the rate of cooling. For hardening, because of the different structures that can be produced, the rate of cooling is exceedingly important. The comparatively rapid cooling required is termed "quenching." This term has a far broader meaning than merely "immersing to cool;" its common use in the sense of extinguish—put out—so indicates. This meaning was carried over into steel treating because of the red heat required—heating above the critical range. Quenching will be described as *relatively rapid cooling*

from temperatures above or within the critical range by the use of mediums more drastic in effect than still air, of which water, oil, molten lead or salts, and an air blast are examples. In this sense the word is commonly used in the literature of steel treating.

Quenching is the final operation in *hardening*, a process that can be described as *heating to temperatures above or within the critical range followed by quenching for the purpose of materially increasing the hardness of steel.*

If the hardness obtained by quenching is greater than desired, modification is possible through a change of internal structure by *tempering* (or *drawing*), a process that can be described as *reheating to some temperature below the critical range subsequent to hardening and cooling at any rate.*

Tempering and drawing are used synonymously, but a distinction has been recognized and will be mentioned later. Because of this, the term "tempering" is sometimes applied to hardening followed by drawing, but such usage should be discouraged. One reason for this is the lack of a term for this complete heat treatment. A term is needed because both drawing and hardening are part of one process of treatment. To this the term "heat treatment," in a narrow sense, is commonly applied but may also include some preliminary process.

Other processes that are directly concerned with changing the structure of steel are included under the general term "annealing." The word "anneal" has a number of meanings, for example "bake" or "fuse," but for heat treatment the common definition is "*to render soft and tough by heating and slowly cooling.*" Softening as opposed to hardening and a slower rate of cooling distinguish annealing processes. Under the term are included processes for refining the crystalline structure by heating to temperatures above the critical range followed by cooling at a slower rate than for hardening. The dividing line between annealing and hardening is not always sharply drawn. Quenching in some slow-cooling medium to obtain a hardness somewhat but not much greater than that resulting from cooling in still air is a border-line process. Softening is desired, but not maximum softness. *Annealing* will be described as *the heating and cooling of steel in the solid state to obtain the maximum or nearly maximum ductility, machinability, or other similar property commonly termed softness; or to refine the crystalline structure without hardening.*

Processes for *softening* by annealing and for refining the crystalline structure will be discussed in detail in a later chapter. Some attention, however, must be given here to processes for refining. Theoretically, refining of the crystalline structure results from heating to temperatures but little above the critical range but, practically, such treatment may result in little or no refining if applied to steel having grains of large size. But by heating to a much higher temperature, well above the critical range, in practice from 200 to 300° F. (110 to 155° C.), or more, above, large grains can be partly reduced in size, and refining can then be completed by the method previously mentioned. This preliminary treatment is seldom necessary for steel of low-carbon content because of the high temperature of the A_{c3} point at which refining takes place.

For convenience the refining of steel by heating to temperatures only slightly above a critical temperature will be termed "grain refining," this being a common usage. The preliminary process has been termed "normalizing" and will be described as *heating to temperatures well above the critical range for the purpose of partly reducing in size crystals too large to be refined by heating to temperatures only slightly above the critical range, and cooling as desired, usually in still air.*

The word "normalizing" implies a process by which steel is made "normal" for further treatment and therefore may be applied to treatments that have objects other than that described. The subject of refining and normalizing requires and will be given considerable discussion. Too many factors enter for a clear, brief description.

In addition to processes that are based upon changes in internal structure, heat treatment includes others that are rather steel-making than steel-treating processes, effecting a change in composition rather than in structure. These processes, however, are governed to a considerable extent by the conditions that have been described and with particular regard to the increase in grain size resulting from overheating.

At one time steel was made from wrought iron by heating the soft iron in charcoal or other carbonaceous material, a process called "cementation." Steel is now made in other ways, but the process has been retained and is now called "carburizing." This term has replaced an older one "carbonizing." Carburizing will be given extended discussion but here will be described as

a process for increasing the carbon content of steel by gradual penetration from the surface as a result of continued contact with hot, active, carbonaceous gases.

Soft steel, low in carbon, can be hardened but slightly. The carbon content at the surface can be increased by carburizing to an amount that makes hardening possible. By stopping the process at the proper point a layer of high-carbon steel is obtained beneath which lies the uncarburized portion of the original steel. Quenching will harden the outer, but not the inner portion. This combination of a hard surface with a soft and ductile interior in one piece finds a wide range of service. Carburizing followed by hardening is a process known as "case hardening." The outer layer, hardened or unhardened, is known as the "case;" the softer inner portion, uncarburized, is called the "core."

The carbon content at the surface may also be increased by contact with molten cyanide salts either by immersion or by sprinkling cyanide salts on the surface of steel heated to the proper temperature. This operation is followed immediately by quenching, the temperature of the molten bath (or of the steel) being regulated to be suitable for hardening. This process is known as "cyaniding."

Nitride of iron replaces carbide of iron (or cementite) in a newly developed process for surface-hardening steel. Carburizing is usually applied to steel of low-carbon content, but nitriding can be used for surface hardening steels much higher in carbon as well as for low-carbon steel. Nitriding may be followed by heat treatment, but hardening is not required, nitride of iron being an exceedingly hard compound. Details will be discussed in connection with hardening, but nitriding will be described here as *a process for the surface hardening of steel by nitrogen through contact with hot ammonia gas.*

Combinations of Processes in Industrial Practice.—Later discussion of steel-treating processes will include others that have not been included here, but this brief description outlines the methods of industrial practice. *Heat treatment,* in the broadest sense, consists of various combinations of individual processes. An outline of these combinations will perhaps present a picture of the methods of practice and permit better discussion of the details. A division will be made between heat treatment after carburizing and direct heat treatment.

COMMON HEAT TREATMENTS CONNECTED WITH CARBURIZING

A	*B*	*C*
Carburize	Carburize	Carburize
Quench (from container)	Quench	Cool in container
	Reheat	Reheat
	Quench	Quench

D	*E*[1]
Carburize	Carburize
Cool in container	Quench
Reheat (for core)	Reheat (for core)
Quench	Quench
Reheat (for case)	Reheat (for case)
Quench	Quench

Final quench may be followed by a draw, but this is not common practice except for special purposes.

[1] Treatment *E* is seldom practiced. Treatments *B* and *C* are the most commonly employed.

HARDENING, ANNEALING, AND DRAWING TREATMENTS

1	2	3	4	5
Heat	Heat	Normalize	Normalize	Anneal
Quench	Quench	Quench	Cool in air	Machine
	Draw	Reheat	Reheat	Heat
		Quench	Quench	Quench
		Draw[1]	Draw	Draw

[1] Draw may be omitted if only hardening required.

6	7[1]	8
Normalize	Normalize	Heat (refine)
Cool in air or quench	Cool in air or quench	Quench
Reheat	Reheat	Anneal
Cool in furnace	Quench	Machine
Machine	Anneal	Heat
Reheat	Machine	Quench
Quench	Heat	Draw
Draw	Quench	
	Draw	

[1] Treatment 7 is seldom used, although sometimes suggested for complete refining.

The common industrial treatments are 1, 2, 5, and 6 and include 3 or 4 when normalizing is desired.

Other combinations are possible. The draw is not always required, as suggested by the difference between 1 and 2.

Applying the Critical-temperature Diagram in Practice.—For these processes, a heating diagram is required, and the critical-temperature diagram of the iron-carbon alloys is so used, although modified for industrial practice and for commercial steels. Because of the difficulty of controlling temperature closely, because of the range of carbon permitted, and for other reasons

that will be explained, the temperatures of practice are well above the A_{c3} point. The leeway permitted in heating must be included in a working diagram. Furthermore, each type of steels requires an individual diagram because of the effect of elements other than iron and carbon by which each type is distinguished. Carbon steel is nearly a pure alloy of iron and carbon but some manganese is always present, because required in manufacturing, and by this element the position of the critical points is altered. Alloying elements not only alter the position of the critical points, but may also affect the structures obtained. Therefore, composition must be considered in discussing steel-treating practice.

NOTE.—Cooling in water or oil after drawing is sometimes referred to as "quenching." Ordinarily, the rate of cooling after drawing, below the critical range, is immaterial, but with some steels greater toughness is obtained by rapidly cooling from the drawing temperature. The end of the A_{r1} point for some steels is so low that drawing temperatures may lie above. "Cool in air" or "cool in water," however, are equally expressive, and "cool" is to be preferred to "quench," indicating less-drastic treatment.

Some steels have critical temperatures well below ordinary atmospheric temperatures and are not governed by the rules that apply to the average, although treatments may be alike.

The use of vague terms is not necessary. Exact information can be conveyed without them, as the following examples indicate, all specifying the same treatment.

Normalize at 1600° F.
Anneal at 1425° F.
Cool in furnace.
Machine.
Harden at 1425° F. in water.
Draw at 900° F.
Cool in air.

Heat to 1600° F.
Cool in air.
Heat to 1425° F.
Cool in furnace.
Machine.
Heat to 1425° F.
Quench in water.
Reheat to 900° F.
Cool in air.

CHAPTER II

COMMERCIAL STEELS COMPOSITION AND WORKING DIAGRAMS

Iron-carbon Alloys and Commercial Steels.—Commercial steels are basically alloys of iron and carbon that contain other elements that are present because derived from the raw material or because added purposely. Some of these elements have no effects upon the position of the critical temperatures, others may have a marked effect if present in comparatively large amount. Their addition to the pure iron-carbon alloys changes the position of the critical temperatures by which heat treatment is guided, usually in proportion to the amount present, and may also alter the results obtained by specific heat treatments. The distinction between the pure iron-carbon alloys may, therefore, depend as much upon the effect of these additional elements as upon difference in composition. These elements, called "alloying elements," are often employed because of the desirable properties that they introduce, and a knowledge of their effect upon the critical temperatures and physical properties of steel is necessary for steel treating.

Carbon Steel and Alloy Steel.—Commercial steels, according to the additional elements present, can be divided into two general classes, carbon steel and alloy steel. Carbon steel comprises alloys that approximate in composition the pure iron-carbon alloys and that, therefore, have nearly the same critical temperatures. Alloy steel contains elements that impart properties not attainable with carbon steel. Chromium, nickel, tungsten, and manganese are the principal alloying elements in commercial steels. Other alloying elements, for example, vanadium and molybdenum, usually present in small amount may be added with these or by themselves. The dividing line between carbon and alloy steel is not sharp. The alloying elements can be present in varying proportions from a small amount, perhaps present naturally because of the raw material, to a comparatively large amount that may have been added

intentionally. In industry, however, certain distinct types are recognized as alloy steels, types that contain relatively large amounts of alloying element or elements added in amount sufficient to have a marked effect.

Effect of Alloying Elements on Critical Temperatures.—The critical-temperature diagram for the pure alloys of iron and carbon (Fig. 7 *c*) is typical for all steels, but the temperature at which the transformations occur may be changed by the addition of alloying elements and in proportion to the amount. Some elements, for example, chromium, raise the critical temperatures; other elements, for example, manganese, nickel, and tungsten, lower them. Steels containing from 12 to 14 per cent of manganese or of tungsten have their critical temperatures far below ordinary atmospheric temperatures. Alloying elements may also change the position of the pearlite point. In the pure iron-carbon alloys, pearlite contained approximately 0.90 per cent of carbon; in some alloy steels the pearlite contains much less carbon. Each type of steel will, therefore, have its own critical-point diagram but nevertheless based on the iron-carbon diagram.

Classification of Steels. S. A. E. Code.—Both carbon and alloy steels are divided into different types according to composition. When only a few types existed, each could be distinguished by the important element, for example, as carbon, nickel, or chrome-nickel steel. If two types contain the same elements but in different amount, they may be distinguished as *high* and *low* or by other similar descriptive adjectives. This method is still in common use, sometimes necessarily, but requires a somewhat lengthy expression. A simple code permits brevity and can be more explanatory if the composition corresponding to a particular symbol is agreed upon generally. Individuals and corporations have used letters and numbers to designate steels but without system and with results as confusing as if different languages were spoken. A common code is necessary and has been supplied by a numbering system, originated by the Pennsylvania Steel Company and, with extensions, made a standard system by the Society of Automotive Engineers. Not all steels have been included, but only those used in the automotive industry. The society specifies the chemical composition under the code number—the more important elements. Steels made to these specifications are known as S. A. E. steels. Each type

and grade, according to carbon range, is given a code number of four (or five) digits, five, if the carbon content requires. The first digit indicates the type or class of steel; the second, the approximate percentage of the principal constituent, although for the carbon steels the second digit may indicate type rather than percentage of alloying element. The last two (or three) digits show the range of carbon.

The S. A. E. Code in Practice.—All elements of importance are specified for S. A. E. steels, including the non-metallic elements sulphur and phosphorus. Some users prefer limits other than those specified for sulphur and phosphorus or may wish to make some other minor change and, therefore, do not use the system. This numbering system, however, supplies symbols for types and for carbon ranges that are generally accepted and can be used regardless of the minor differences in other elements. For example, the X. Y. Z. Company may use the system but indicate by a prefix X. Y. Z. a deviation from S. A. E. specified analysis, a method that is quite common.

The numbering system also permits designation of a narrower range of carbon than ordinarily specified. Standard practice specifies a range of 0.12 per cent or 12 points of carbon (including the first and last figures that set the range). Such a range is sometimes too wide for accurate heat treating, and a narrower range will, therefore, be preferred. This can be specified by means of some number intermediate between standards. For example, a range of from 0.35 to 0.40 carbon in carbon steel would be indicated by the number 1037.

Types of Commercial Steels in S. A. E. List.—The recognized types of commercial steels according to the S. A. E. standard and the indicating digits are as follows:

1. Carbon steels (including types with higher manganese).
2. Nickel steels.
3. Nickel-chromium steels.
4. Molybdenum steels.
5. Chromium steels.
6. Chrome-vanadium steels.
7. Tungsten steels.
8. (Not yet assigned.)
9. Silico-manganese steels.

These types by no means include all that have been made or all that are on the market. For example, no reference is made

to manganese steel. The S. A. E. list includes only those types and steels used particularly in the automotive industry.

A list of S. A. E. standard steels with the specified analysis will be given but will be supplemented by reference to steels not listed but of use in industry, and deviations from these analyses and in listing will be considered.

Carbon Steels:

CARBON STEELS

S. A. E. steel number	Carbon range	Manganese range	Phosphorus, maximum	Sulphur, maximum
1010	0.05 to 0.15	0.30 to 0.60	0.045	0.055
1015	0.10 to 0.20	0.30 to 0.60	0.045	0.055
1020	0.15 to 0.25	0.30 to 0.60	0.045	0.055
1025	0.20 to 0.30	0.50 to 0.80	0.045	0.055
1030	0.25 to 0.35	0.50 to 0.80	0.045	0.055
1035	0.30 to 0.40	0.50 to 0.80	0.045	0.055
1040	0.35 to 0.45	0.50 to 0.80	0.045	0.055
1045	0.40 to 0.50	0.50 to 0.80	0.045	0.055
1050	0.45 to 0.55	0.50 to 0.80	0.045	0.055
1095	0.90 to 1.05	0.25 to 0.50	0.045	0.055
X1315	0.10 to 0.20	1.25 to 1.55	0.050	0.085 to 0.135
1350*	0.45 to 0.55	0.90 to 1.20	0.040	0.055
1360*	0.55 to 0.70	0.90 to 1.20	0.040	0.055

* The silicon content of steels to 1350 and 1360 shall not exceed 0.30 per cent.

SCREW STOCK

S. A. E. steel number	Carbon range	Manganese range	Phosphorus	Sulphur range
1112	0.08 to 0.16	0.60 to 0.80	0.09 to 0.13	0.08 to 0.155
1120	0.15 to 0.25	0.60 to 0.90	0.06 maximum	0.08 to 0.155

STEEL CASTINGS

As required by physical properties...	0.05 maximum	0.055 maximum

Steels between 1050 and 1095 are not used extensively in the automotive industry but are important, for example:

Type	Carbon, range	Manganese, range	Phosphorus	Sulphur
1070	0.65 to 0.75	0.50 to 0.80	0.40 maximum[1]	0.50 maximum[1]
1080	0.75 to 0.90	0.50 to 0.80[1]	0.04 maximum[1]	0.05 maximum[1]

[1] Other specifications exist in practice.

Carbon Spring Steels.—Because these steels are not included in the S. A. E. and other standard lists, they are frequently overlooked. 1060, 1070, and 1080 are primarily spring steels, although used for other purposes. 1080 is extensively employed in agricultural implements—cultivator shovels and harrow teeth, for example—in bumpers for motor cars and trucks, and other products that require a "spring temper"—hardness with flexibility. For some purposes—leaf springs, for example—1095 steel is preferred. The higher carbon steel is somewhat more easily hardened, a point that is occasionally of importance in heat treating pieces of large section. The other spring steels, however, give more uniform results when heat treated. The danger of breakage in cold weather is less with the lower-carbon range. Certain desirable combinations of hardness and toughness are more easily obtained with steels in the range between 1050 and 1095, and such steels should not be overlooked in practice.

Acid Open-hearth Steels.—In the manufacture of S. A. E. steels, any standard method is presumably allowed, but the analyses of the steels from 1015 to 1095 indicate either the basic open hearth or electric furnace, crucible steel being out of the question because of cost. Sulphur and phosphorus, because of their acid reaction, can be lowered in the basic open-hearth or electric furnace but not in the acid open hearth. Acid open-hearth steel is more expensive than basic open-hearth steel but is comparatively free from oxides, is uniform, and gives better results, judging from tests and life in service. Although sometimes specified for heat-treated products, acid open-hearth steel finds it largest fields in rope wire, locomotive tires, and other untreated products that perform heavy duty. This steel also enters the market rerolled to form, used locomotive tires being a typical raw material for the rerolled product. Sulphur and phosphorus, acid elements, are not removed in the acid open-hearth furnace, and the amount present in the steel will depend upon the amount present in the raw material from

which the steel is made. More of these elements will usually be found in acid open-hearth than in basic open-hearth steel. The upper limit for sulphur and phosphorus is about 0.08 per cent in acid open hearth as compared with 0.05 or 0.055 for sulphur and 0.045 and 0.05 for phosphorus in basic open-hearth steel.

Screw Stock.—Steel containing less than about 0.25 per cent of carbon is not easily machined, particularly if speed is desired. Such steel when cast or hot rolled is so soft that a cutting tool operating at even a reasonably high speed tears rather than cuts the surface. Increasing the hardness improves the machinability, and cold drawing is often employed for that purpose if low-carbon steel is supplied in the form of rod. The hardness that can be so obtained, however, is limited. Low-carbon steel can be made more machinable by incorporating in the steel small particles of manganese sulphide, a compound of sulphur and manganese. The additional sulphur required and the maganese necessary to balance it are added in the ladle.

The list of S. A. E. steels contain the two representative examples of screw stock, as follows:

S. A. E. steel number	Carbon, range	Manganese, range	Phosphorus	Sulphur, range
1112	0.08 to 0.16	0.60 to 0.80	0.09 to 0.13	0.08 to 0.155
1120	0.15 to 0.25	0.60 to 0.80	0.06 maximum	0.08 to 0.155

Steel 1112 is made by the Bessemer process; steel 1120, by the basic open-hearth process. Phosphorus is not removed in the Bessemer process—in this country an acid process—but is removed in the basic open hearth. The two steels are, therefore, distinguished by a difference in the content of phosphorus. For machinability alone Bessemer screw stock is better than basic open hearth because of the hardening effect of the greater amount of phosphorus and because a greater amount of other non-metallic materials is usually present. Small particles of slag, for example, or oxides also improve machinability. The cleaner basic open-hearth screw stock is generally preferred.

Screw stock is heat treated only by carburizing and hardening or by cyaniding, and comparatively little finds its way into the hardening room even for such treatment. On the other hand, sulphur is sometimes added to alloy steels that are heat treated,

hardened and drawn, as well as carburized and hardened. S. A. E. X1315 is practically an alloy steel, with manganese as the alloying element, a carburizing steel containing sulphur to improve machinability.

Working-temperature Diagram for Carbon Steels.—The true carbon steels are like the corresponding alloys of iron and carbon but usually contain manganese in an amount sufficient to affect the position of the critical temperatures and, also, to change the position of the pearlite point, as illustrated in Fig. 9, the working diagram for carbon steels. The change in the position of the critical points will be evident if a comparison is made with the

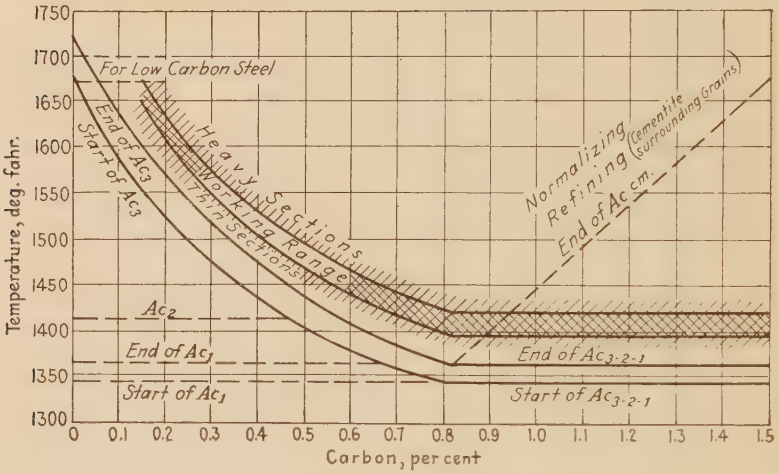


FIG. 9.—Working critical temperature diagram. Carbon steels, 1000 type.

heating curves and corresponding critical-point diagram of the pure alloys of iron and carbon, for example Figs. 6 (*b*) and 7 (*b*). The critical temperatures are lower, and the percentage of carbon in pearlite is somewhat less. A working range, above the end of the A_{c3} transformation, is provided, indicating an allowance that has been found necessary in industrial heat treating. Small pieces and pieces of thin section can be heated to temperatures not much above the A_{c3} point, but large pieces require heating to higher temperatures for hardening in order to increase the depth of hardening and, also, to reduce the time required. Temperatures well above the working range may be used if heating does double duty in softening to permit forming and in raising the temperature above the critical range so that it can be

hardened by rapid cooling. If steel is to be formed and hardened in one heating operation, some allowance must be made for cooling off in forming. Rapid cooling for hardening must begin at a temperature above the A_{c3} point, and, therefore, the temperature at which the forming operation is finished must not be below this point. The latitude permitted simplifies steel-treating practice but must not be taken as license for overheating beyond the allowable range.

Effect of Heating above the Critical Range.—Theoretically, the temperature of heating should not go above the A_{c3} point because of the increase in grain size that accompanies such overheating and other results that affect the properties obtained. So much stress has been laid upon the danger of overheating that the practical side is often overlooked. No abrupt and marked increase in grain size results from heating to temperatures just beyond the A_{c3} point; the grain size obtained will increase as the temperature rises above the critical range, but the change is so gradual that temperatures well above the critical range can usually be employed without much effect upon the final results in service. The allowance for temperature that is made in practice will depend upon the kind of steel to be treated, size of the piece, and other factors, but temperatures 100 or 150° F. (55 or 85° C.) above the critical range are commonly employed. The effect of such higher temperatures and the allowable range are pictured in the diagrams of Fig. 42 in the chapter discussing hardening. That these higher temperatures do no harm is fortunate because of the difficulty if not the impossibility of heating within a very narrow range of temperature and, also, because steel makers require some latitude in carbon content. In the specifications of the S. A. E. steels, a "10-point" range (practically 12 including the upper and lower point of the range) is allowed. For example, 1035 steel allows a range of carbon from 0.30 to 0.40 per cent. For heat treating this steel, the temperature required for a carbon content of 0.30 per cent would be specified, this being the highest temperature of the range and, therefore, high enough for the whole range. For the other end of the range, .40 carbon, this temperature is higher than necessary but is within the permissible limit.

Pearlitic-manganese Steels.—Steels in the 13 series of the S. A. E. numbering system are not plain carbon steels, to be exact, because manganese is here used as a distinctly alloying

element. These steels are, therefore, to be considered as alloy steels, although the line between them and plain carbon steels is not sharp. Manganese is a hardening element, but the amount that is present in plain carbon steels is comparatively small and can be neglected unless the carbon content is also high. In high-carbon steel, particularly tool steel, the hardening effect of manganese has led to specifications reducing the amount of that element below that allowed in steels of lower carbon. Note the specification for 1095 steel. The effect of manganese becomes notable when the amount present goes above 1 per cent.

Manganese has served as an alloying element in tool steel for some time. By increasing the manganese to 1.25 per cent or more, the less drastic oil quenching can replace water quenching. Hardening carbon tool steel in water often results in distortion and shrinking, but for such steel water may be required to obtain sufficient hardness. Steel containing more manganese, on the other hand, can be hardened satisfactorily in oil and with less shrinkage and distortion. Such steel is called "non-shrinking." Manganese has also become an important alloying element for structural steel. Typical ranges for manganese lie between 0.90 and 1.90. For example:

Type	Carbon range	Manganese range	Silicon range	Phosphorus, maximum	Sulphur, maximum
1335	0.30 to 0.40	1.60 to 1.90	0.15 to 0.30	0.040	0.050
1345	0.40 to 0.50	1.60 to 1.90	0.15 to 0.30	0.040	0.050
1355	0.50 to 0.60	0.90 to 1.20	0.15 to 0.30	0.040	0.050

To steels of this type the name "manganese steel" could be applied, but this term has already been given to another type of steel containing from 10 to 15 per cent of manganese. High-manganese steel is a solid solution at ordinary atmospheric temperatures, and the lower-manganese steels are, therefore, sometimes described as "pearlitic manganese steel," but this type has been given no generally accepted name.

Manganese Steel.—Steels containing between about 3 and about 7 per cent of manganese are too hard and brittle for service, but when the content of manganese has been increased to at least 10 per cent, marked toughness and resistance to abrasion result. Steels containing between 12 and 15 per cent of manga-

nese find service in rails for curves, frogs, switch points, rolls, stamps, face plates for electromagnets, and other duty of the same kind that requires a combination of toughness and resistance to abrasion. The average content of manganese is 12 per cent; of carbon, 1 per cent. The critical temperature range is well below ordinary atmospheric temperatures, so that this type of steel ordinarily forms a solid solution. Such steel is non-magnetic and does not follow the rules that control the heat treatment of ordinary commercial steels. The peculiar properties are brought out by quenching from 1825° F. (1000° C.) in cold water and as rapidly as possible, a toughening rather than a hardening treatment. Continued pounding in service changes the structure of the solid solution to a harder form.

Effect of Manganese on the A_{r3} and Pearlite Points.—Manganese moves the pearlite point to the left. For iron-carbon alloys, this point is approximately 0.90 per cent of carbon. When 1 per cent of manganese is present, the pearlite point is lowered to approximately 0.80 per cent of carbon; for 2 per cent of manganese, to approximately 0.70 per cent of carbon. Up to 1 per cent of manganese, the A_r3 point is lowered by about 115° F. (64° C.) for 1 per cent of manganese. For a content between 1 and 2 per cent manganese lowers the $Ac3$ point *b* about 10° F. (5° C.) for an increase of 1 per cent.

S. A. E. Nickel Steels.—Two types are given in the S. A. E. list, one averaging 3.5 per cent of nickel, the other, 5 per cent.

NICKEL STEELS

S. A. E. steel number	Carbon range	Manganese range	Phosphorus, maximum	Sulphur, maximum	Nickel range
2015	0.10 to 0.20	0.30 to 0.60	0.04	0.05	0.40 to 0.60
2115	0.10 to 0.20	0.30 to 0.60	0.04	0.05	1.25 to 1.75
2315	0.10 to 0.20	0.30 to 0.60	0.04	0.05	3.25 to 3.75
2320	0.15 to 0.25	0.30 to 0.60	0.04	0.05	3.25 to 3.75
2330	0.25 to 0.35	0.50 to 0.80	0.04	0.05	3.25 to 3.75
2335	0.30 to 0.40	0.50 to 0.80	0.04	0.05	3.25 to 3.75
2340	0.35 to 0.45	0.50 to 0.80	0.04	0.05	3.25 to 3.75
2345	0.40 to 0.50	0.50 to 0.80	0.04	0.05	3.25 to 3.75
2350	0.45 to 0.55	0.50 to 0.80	0.04	0.05	3.25 to 3.75
2512	maximum 0.17	0.30 to 0.60	0.04	0.05	4.75 to 5.25

Other typical commercial nickel steels are:

Type	Carbon	Manganese	Nickel	Silicon	Phosphorus, maximum	Sulphur, maximum
2015	0.10 to 0.20	0.30 to 0.60	0.40 to 0.60	0.15 to 0.30	0.04	0.05
2115	0.10 to 0.20	0.30 to 0.60	1.25 to 1.75	0.15 to 0.30	0.04	0.05

Of these, 2015 contains too little nickel for general classification as a nickel steel. This steel is a carburizing steel and replaces plain carbon steel for oil hardening because more uniform hardness can be obtained. 2115 is also a carburizing steel.

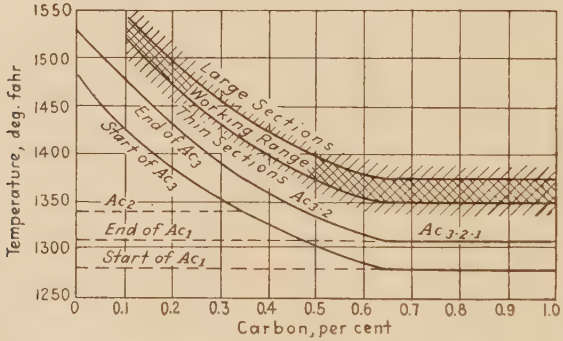


Fig. 10.—Working critical temperature diagram. 3½ per cent nickel steels, 2300 type.

The working critical-temperature diagram for 3.5 per cent nickel steel is shown in Fig. 10. The lowering of the critical temperatures and the change in position of the pearlite point as a result of adding nickel can be seen by comparison with Fig. 9. Corresponding critical temperatures are about 50° F. (about 30° C.) lower, and the pearlite point has moved to 0.65 per cent of carbon. The critical temperatures of 5 per cent nickel steel are about 25 to 30° F. (about 15° C.) lower than the corresponding temperatures of 3.5 per cent nickel steel. The addition of nickel increases hardness without much effect upon the ductility. Nickel steels are known for toughness, for resistance to dynamic stresses.

Chromium Steels.—The chromium steels listed in the S. A. E. specifications are representative, although variations from these specifications will be found. Chromium is primarily a hardening

element, an element of importance in tools where hardness is desirable. It is a prominent element in steel for safes, for stamps in ore crushing, dies, and other service that requires great hardness and deep hardening. Chromium steels are used almost entirely for ball and roller bearings, 52100 being primarily a steel for balls and rollers, cones and races. Low-carbon chrome steel is used for such parts when carburizing is desirable. Chromium also finds service in steel for permanent magnets.

S. A. E. CHROMIUM STEELS

S. A. E. steel number	Carbon range	Manganese range	Phosphorus, maximum	Sulphur, maximum	Chromium range
5120	0.15 to 0.25	0.30 to 0.60	0.04	0.05	0.60 to 0.90
5140	0.35 to 0.45	0.50 to 0.80	0.04	0.05	0.80 to 1.10
5150	0.45 to 0.55	0.50 to 0.80	0.04	0.05	0.80 to 1.10
52100	0.95 to 1.10	0.20 to 0.50	0.03	0.035	1.20 to 1.50

Still higher percentages of chromium will be found in the tool steels, a common steel for hot work, particularly in dies, containing 3.50 to 4.00 per cent of chromium and 0.80 to 0.90 per cent of carbon. More attention will be given to such steels in discussing tool hardening. Steels containing from 12 to 14 per cent of chromium and 1.00 per cent of carbon, another type containing 2.00 per cent, have also found service in tools. Steels containing this large amount of chromium resist weathering, however, and are practically rustless in ordinary service, although attacked by strong acids and alkalies. Because of this, the high-chromium steels are known as "stainless steels." The carbon content of stainless steel varies. Representative ranges are 0.10 to 0.20 per cent, 0.20 to 0.30 per cent.

Molybdenum with Nickel or Chromium.—Molybdenum is an element that has recently been introduced and is the only alloying element that is not imported. Molybdenum is not, however, one of the principal alloying elements but is an addition agent used with other alloying elements. In the S. A. E. list below, molybdenum will be found with nickel and again with chromium. Molybdenum apparently is a toughening element particularly when combined with chromium. It has found

service in tool steels as well as in structural steels. Statements have been made that the addition of molybdenum increases machinability, but this is difficult to prove because of the lack of a definite standard. One very noticeable advantage lies in the ease with which scale is removed after forging or hot rolling.

S. A. E. Molybdenum Steels

S. A. E. steel number	Carbon range	Manganese range	Phosphorus, maximum	Sulphur, maximum	Chromium range	Nickel range	Molybdenum range
4130	0.25 to 0.35	0.40 to 0.70	0.04	0.05	0.50 to 0.80	.....	0.15 to 0.25
4140	0.35 to 0.45	0.40 to 0.70	0.04	0.05	0.80 to 1.10	.....	0.15 to 0.25
4150	0.45 to 0.55	0.40 to 0.70	0.04	0.05	0.80 to 1.10	.....	0.15 to 0.25
*4615	0.10 to 0.20	0.30 to 0.60	0.04	0.05	.....	1.50 to 2.00	0.20 to 0.30

* Silicon range 0.15 to 0.30.

Chromium-vanadium Steels:

S. A. E. Chromium-vanadium Steels

S. A. E. steel number	Carbon range	Manganese range	Phosphorus, maximum	Sulphur, maximum	Chromium range	Vanadium	
						Minimum	Desired
6120	0.15 to 0.25	0.30 to 0.60	0.04	0.045	0.80 to 1.10	0.15	0.18
6125	0.20 to 0.30	0.50 to 0.80	0.04	0.045	0.80 to 1.10	0.15	0.18
6130	0.25 to 0.35	0.50 to 0.80	0.04	0.045	0.80 to 1.10	0.15	0.18
6135	0.30 to 0.40	0.50 to 0.80	0.04	0.045	0.80 to 1.10	0.15	0.18
6140	0.35 to 0.45	0.50 to 0.80	0.04	0.045	0.80 to 1.10	0.15	0.18
6145	0.40 to 0.50	0.50 to 0.80	0.04	0.045	0.80 to 1.10	0.15	0.18
6150	0.45 to 0.55	0.50 to 0.80	0.04	0.045	0.80 to 1.10	0.15	0.18
6195	0.90 to 1.05	0.20 to 0.45	0.03	0.035	0.80 to 1.10	0.15	0.18

These steels, with a wider range in the carbon content, parallel those of the chrome steels of the 51 series. Vanadium, like molybdenum, is an additional element but has an advantage in being an excellent deoxidizer. The claims for vanadium are improved machinability and a general improvement in physical properties, also a small grain size.

Working-temperature Diagram for Chromium-nickel Steel.—The critical-temperature working diagram for chromium steels is given in Fig. 11. The effect of chromium in raising the critical temperatures is evident. Chromium-molybdenum and chromium-vanadium steels are included in the diagram, as these elements do not affect the critical temperatures, although

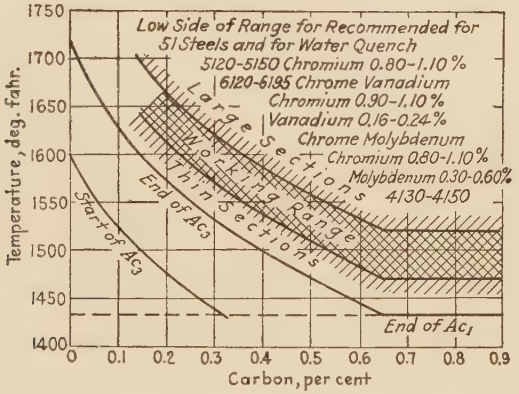


FIG. 11.—Working critical temperature diagram. Chromium steels.

they may affect the working temperatures, as indicated in the diagram. Both molybdenum and vanadium increase the working range.

Chromium-nickel Steels.—Between the steels with nickel element and those with chromium as the only alloying element lie the chromium-nickel steels, more commonly called "chrome-nickel steels." Chromium and nickel together found service in some of the first alloy steels made, and the combination has long been recognized as excellent because each element not only introduces its own peculiar qualities but also increases the effect of the other. The chromium-nickel steels, however, have received considerable competition from other types, particularly from chromium with molybdenum or vanadium. The S. A. E. list is as follows:

S. A. E. Nickel-chromium Steels

S. A. E. steel number	Carbon range	Manganese range	Phosphorus, maximum	Sulphur, maximum	Nickel range	Chromium range
3115	0.10 to 0.20	0.30 to 0.60	0.04	0.05	1.00 to 1.50	0.45 to 0.75
3120	0.15 to 0.25	0.30 to 0.60	0.04	0.05	1.00 to 1.50	0.45 to 0.75
3125	0.20 to 0.30	0.50 to 0.80	0.04	0.05	1.00 to 1.50	0.45 to 0.75
3130	0.25 to 0.35	0.50 to 0.80	0.04	0.05	1.00 to 1.50	0.45 to 0.75
3135	0.30 to 0.40	0.50 to 0.80	0.04	0.05	1.00 to 1.50	0.45 to 0.75
3140	0.35 to 0.45	0.50 to 0.80	0.04	0.05	1.00 to 1.50	0.45 to 0.75
3215	0.10 to 0.20	0.30 to 0.60	0.04	0.045	1.50 to 2.00	0.90 to 1.25
3220	0.15 to 0.25	0.30 to 0.60	0.04	0.045	1.50 to 2.00	0.90 to 1.25
3230	0.25 to 0.35	0.30 to 0.60	0.04	0.045	1.50 to 2.00	0.90 to 1.25
3240	0.35 to 0.45	0.30 to 0.60	0.04	0.045	1.50 to 2.00	0.90 to 1.25
3245	0.40 to 0.50	0.30 to 0.60	0.04	0.045	1.50 to 2.00	0.90 to 1.25
3250	0.45 to 0.55	0.30 to 0.60	0.04	0.045	1.50 to 2.00	0.90 to 1.25
3312	maximum 0.17	0.30 to 0.60	0.04	0.045	3.25 to 3.75	1.25 to 1.75
3325	0.20 to 0.30	0.30 to 0.60	0.04	0.045	3.25 to 3.75	1.25 to 1.75
3335	0.30 to 0.40	0.30 to 0.60	0.04	0.045	3.25 to 3.75	1.25 to 1.75
3340	0.35 to 0.45	0.30 to 0.60	0.04	0.045	3.25 to 3.75	1.25 to 1.75
3415	0.10 to 0.20	0.30 to 0.60	0.04	0.045	2.75 to 3.25	0.60 to 0.95
3435	0.30 to 0.40	0.30 to 0.60	0.04	0.045	2.75 to 3.25	0.60 to 0.95
3450	0.45 to 0.55	0.30 to 0.60	0.04	0.045	2.75 to 3.25	0.60 to 0.95

Of these steels the 3135 series, particularly those containing between 0.25 and 0.45 per cent of carbon, are used the most because they are as satisfactory for the service demanded as the others and less expensive. This series is of interest because first introduced into industry as a natural alloy steel made directly from ore containing nickel and chromium, a steel known as "Mayari," a term that still persists in the iron foundry. This steel was immediately successful because it could meet requirements for which steels with larger amounts of alloying element, and more expensive, had previously been required. To meet the demand for a steel of this type, steel makers produced a steel of similar analysis, first known as "synthetic Mayari." The average content of chromium and nickel is now slightly higher in the synthetic steel than in the natural Mayari. Perhaps because of this, occasional variation from the S. A. E. specifications will be found. This list omits some ranges of carbon that are in commercial use, for example 3145 or 3150, like 3140, except for the carbon range, steels sometimes

used for gears. 3145 (or 3150) is an excellent steel for forging dies and other tools.

Working-temperature Diagram for Chromium-nickel Steel.—The critical-temperature working diagram for steels in the 31 series is shown in Fig. 12. The effect of nickel in lowering the critical temperatures has been offset by the chromium.

The steels of the 33 series represent an early type primarily intended for armor plate, carburized, but gradually brought into general structural uses with a wider range of carbon. General purposes, however, are met satisfactorily by less expensive steels. The critical temperatures of steels in this series approxi-

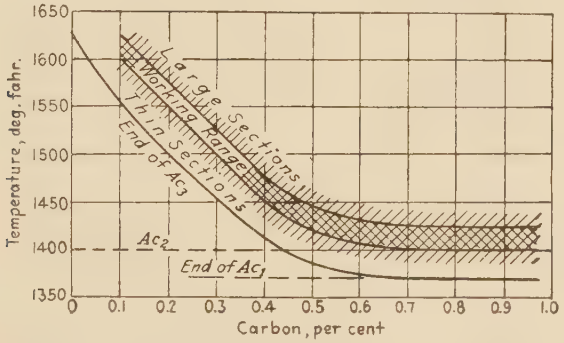


FIG. 12.—Working critical-temperature diagram. Low chromium-nickel steels, 3100 type.

mate about 25° F. (15° C.) below those of the corresponding members of the 31 series. The critical temperatures of steels in the 34 series are about 45° F. (25° C.) lower than corresponding points in the 31 series. This statement is not exact but is serviceable for working purposes.

TUNGSTEN STEELS

S. A. E. steel number	Carbon range	Manganese, maximum	Phosphorus, maximum	Sulphur, maximum	Chromium range	Tungsten range
71360	0.50 to 0.70	0.30	0.035	0.04	3.00 to 4.00	12.00 to 15.00
71660	0.50 to 0.70	0.30	0.035	0.04	3.00 to 4.00	15.00 to 18.00
7260	0.50 to 0.70	0.30	0.035	0.04	0.50 to 1.00	1.50 to 2.00

Tungsten Steels.—The most important service rendered by tungsten is in tool-steel (high-speed steel) containing 12 per

cent or more, as illustrated in the specifications given. In practice, the composition of high-speed tool steel is rarely specified, this material being bought under the brands of the different makers because they are primarily responsible for the service obtained. Compositions vary in detail, but those given are representative. Tungsten in much lower amount, with from 1 to 3 per cent typical, is present, with other alloying elements, notably chromium, in tool steels intended for special duties. Tungsten in valves for internal-combustion engines reduces burning and warping.

Silico-manganese Steels.—In these steels, silicon is the predominating alloying element, the manganese content being but little higher than in the ordinary carbon steels. Silico-manganese steels are among the oldest alloy steels and were once used for gears until replaced by the newer types of alloy steels. Now it is primarily a spring steel. Standard types are listed.

SILICO-MANGANESE STEELS

S. A. E. steel number	Carbon range	Manganese range	Phosphorus, maximum	Sulphur, maximum	Silicon range
9250	0.45 to 0.55	0.60 to 0.90	0.045	0.05	1.80 to 2.20
9260	0.55 to 0.65	0.60 to 0.90	0.045	0.05	1.80 to 2.20

These steels require higher temperatures for hardening than the other standard steels listed, high-speed steel excepted, specification ranging from 1550° F. (845° C.) to 1650° F. (900° C.). The A_{c3} point of silicon steels is not easily located. The A_{c1} point is raised 50° F. (28° C.) by 1 per cent of silicon.

Magnet Steels.—These steels by no means complete the list of commercial steels, a list that is constantly increasing as new alloying elements and new processes are developed. A recent development is the use of aluminum in steel to be nitrided, a development which will be discussed in the chapter on hardening. Aluminum has had long service as a deoxidizer. Of interest are the steels for permanent magnets of which there are several types. Representative magnet steels may contain chromium, tungsten, cobalt, and other elements alone or in combination, as shown in the following table:

MAGNET STEELS

Carbon	0.65	0.85	0.90	0.4 to 0.8	0.8 to 1.0	1.0	1.0	0.50
Manganese	0.25	0.35	0.30	.....	1.0	3.5	1.5	
Chromium	0.70	2.00	2.00	1.5 to 3.0	5.0 to 6.0	5.0	9.0	2.0
Tungsten	5.50	1.00	....	5.0 to 9.0	.....	....	....	8.0
Cobalt	....	....	....	30 to 40	35.0	35.0	15.0	9.0 to 18.0

The cobalt steels must be heated rapidly to the quenching temperature to avoid the formation of graphite. These steels are heated to 1750 to 1825° F. (950 to 1000° C.), a narrower range for high carbon, 1690 to 1760° F. (920 to 960° C.). For quenching, the cobalt is neglected and the medium selected according to the type of the steel. A close control of the temperature of the quenching medium is often necessary. The tungsten and chromium magnet steels have a hardening temperature approximately 1450° F. (790° C.). These steels are aged after hardening by holding in boiling water a few minutes and then cooling in ice water, repeating ten to fifteen times.

MINOR ELEMENTS

Specifications for the composition of steel include reference to elements that have little or no effect upon steel-treating practise either because of their nature or because present in too small amount. Those most commonly mentioned are manganese, not as an alloy, sulphur, phosphorus, and silicon, elements that are derived from the ore or added purposely.

Manganese as a General-purpose Element.—Of these elements manganese is the most important, not as an alloying element alone, but because essential in the manufacture of steel as a deoxidizer and a base with which sulphur can combine. Oxygen is taken up by steel in the process of melting but can be removed by manganese and carried to the slag. Any excess of manganese beyond that required for the oxygen or sulphur present dissolves in the steel. Even the small amount present in the true carbon steels has an alloying effect and increases the hardness that can be obtained by heat treatment. Too much manganese in high-carbon steel is often responsible for *water cracks* when such steel is hardened by rapid cooling in water. For this reason, the manganese content is kept as low as possible in high-carbon steel, particularly tool steel. For example, the manganese specified in S. A. E. 1095 steel is 0.25 to 0.50, a reduction from

the 0.50 to 0.80 range allowed in other steels. The manganese content is also comparatively low for low-carbon steels, 1015 to 1025, but this is due to the fact that carbon is usually added in the manufacture of steel by means of a manganese alloy, and the manganese content, therefore, tends to be lower for the lower-carbon ranges.

Silicon.—Of the non-metallic elements, silicon, sulphur, and phosphorous, silicon is of importance because an alloying element, as already described. It is also a deoxidizer. This element is present in pig iron from which it is removed in the steel furnace, entering the slag. Silicon was once determined for the purpose of detecting slag in steel and, therefore, limited, "not over 0.20 silicon" being the usual specification. Recognition is given, however, to its deoxidizing quality, and a limiting specification is now usually omitted, this being left to the steel maker. Specification is now more for the purpose of having some present. Up to 0.50 or 0.60 per cent silicon seems to have no particular effect upon properties.

Phosphorus and Sulphur.—Phosphorus and sulphur are usually classed together, because both enter from the ore. Both are acid-forming elements and, therefore, are not removed in the acid-bessemer process used in this country, but both can be removed, at least in part, in the basic open-hearth furnace, phosphorus more easily. Because of a demand for low sulphur and phosphorus, the basic open-hearth furnace has replaced the bessemer to a considerable degree, bessemer ores low in these elements having become scarce. Phosphorus is a hardening element but is usually present in small amount so that its effect is of no particular importance. Any gain in hardness obtained by its use is apparently offset by an increase in brittleness. The line is hard to draw, but the limit of phosphorus is usually set at 0.08 per cent, although steels containing twice that amount have given excellent service.

Sulphur has received more attention than the other non-metallic elements and has been the subject of much controversy. The objection to sulphur goes back to an earlier stage in the manufacture of steel, when it was discovered that sulphur was responsible for *red-shortness*, the crumbling of steel when rolled hot. This was found to be due to the formation of iron sulphide, a compound of iron and sulphur that has a comparatively low melting point. But it was discovered that the mainstay of the

steel maker, manganese, would combine with sulphur and break up the combination with iron. Manganese, therefore, has another function, to combine with sulphur to form manganese sulphide. But in spite of the removal of the danger of red-shortness, sulphur still remained under the ban in spite of the excellent service rendered by screw stock. Specification has set the limit as low as 0.03 or 0.035. The removal of sulphur to this low limit in the basic open-hearth furnace has been responsible for unrecognized trouble, probably due to oxygen, as a result of the forcing. The demand for acid open-hearth steel, with comparatively high sulphur and phosphorous, was also overlooked. The general harmlessness of manganese sulphide, however, particularly if present in very small globules, is generally recognized and the limit of sulphur has steadily risen. The standard is now 0.055 for basic open-hearth steel, from 0.045 in a few years. The limit is still held down in tool steel, usually 0.04. Alloy steels are usually more carefully made than carbon steels and from selected raw materials, so that 0.045 or 0.05 per cent is not hard to obtain. It is probable that the quality of steel is improved by avoiding the forcing of lower sulphur.

Oxygen.—Oxygen is a very undesirable element in steel, one that is probably responsible for more trouble than both sulphur and phosphorus. Unfortunately, there is no quick, accurate method for determining oxygen, but much work has been done to determine its effect, work that practically proves that very small amounts can be responsible for much trouble. Oxygen is more easily absorbed by steel in the basic open-heart furnace than in furnaces with an acid (silica) lining. Its effect has long been recognized, and aluminum has been commonly employed as a deoxidizer for basic steel, although this may introduce some other problems. The normally small amount of non-metallic inclusions that steel may contain have far less effect upon the properties and service of steel than oxygen.

CHAPTER III

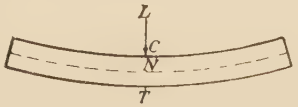
PHYSICAL PROPERTIES AND THE STRESSES OF SERVICE

Physical Properties.—The principal object of steel treating is some desirable and definite condition that can be approximately described by such terms as "hard" and "soft" or by some combination of terms such as "hard and tough." The condition of steel, desirable or undesirable, has long been described by these terms and combinations of terms. Hard and brittle, soft and tough describe physical properties that are easily recognized, particularly if some standard of comparison exist —for example, "hard as glass." Under some conditions, these terms are satisfactory enough, but modern engineering and manufacturing practice requires physical conditions that are not so easily described, conditions that cover the entire range between two opposite extremes—hard and soft, for example. Within this range, differences in condition may be comparatively slight but of importance in practice. Some accurate standard of measurement is required by which even slight differences in physical condition can be distinguished, a standard that will be fairly representative of the requirements of service.

Stress and Strain. The Stresses of Service.—In service, steel and other materials must resist stresses of various kinds. A *stress* can be defined as a force that changes the form of a body either temporarily or permanently. The result of applied stress is a *strain*, an alteration produced by stress. Stress is required to bend a bar of steel, the change of shape or deformation is strain. If, for example, a bar of steel 1 in. in length and 1 sq. in. in cross-sectional area stretches 0.001 in. under a pull of 30,000 lb., the stress is 30,000 lb. and the strain is 0.001 in. The unit stress is 30,000 lb. per square inch. Stress and strain are not always clearly distinguished and are sometimes used as synonymous terms, but the distinction should be clear. Stress may be static or dynamic. Static stresses are slowly applied. Examples of static stresses include tensile (stress under pull), compressive, torsional (twisting), transverse (bending), and

shearing (the sliding of one part over an adjacent part). Dynamic stresses are suddenly applied, as by a blow or by rapidly repeated bending, for example.

Stress under torsion is fundamentally shearing stress, and shear enters into tensile and compressive stress and into transverse stress, which can also be resolved into compressive and tensile stress. For example, sketch *A* illustrates the effect of transverse stress from load *L* applied vertically at the center of a bar supported at both ends. At *C*, the stress is compressive; at *T*, tensile; and at *N*, no stress exists. The tensile stress increase from *N* to *T*, and the compressive stress, from *N* to *C*, with maximum stress at *T* and *C*. The local stress will be greater if the same load is applied at one end of the bar, the other end being fixed. The stress will be much greater if a *live* load is applied, for example by a falling weight, than if the load is dead (applied without impact). The difference is marked even if the impact is comparatively small.



The Tensile Test and Tensile Properties.—For static loads, and sometimes for dynamic, measurement of stress is based upon unit stress—for example, pounds per square inch. Laboratory methods have been devised to determine the resistance of materials to unit stress. Of these methods the tensile test is the standard for general comparison. In this test, a bar of standard dimensions is placed in a tensile-testing machine, equipped with a weighing beam, and is subjected to a gradually increasing and continually measured load until pulled apart. From the start, the test bar increases slightly in length, but not noticeably, and in proportion to the load applied. In this stage, the bar will return to the original length if released. But, if the load continually increases, a sudden and marked increase in length, out of proportion to the increase in load, will eventually occur and remain, if the bar is released, a permanent set. The load at which this permanent set first occurs is called the "elastic limit." Beyond the elastic limit the bar stretches rapidly with a comparatively smaller increase in load until the bar breaks. The load at which fracture occurs is called the "tensile strength" (or "ultimate" or "maximum strength").

To determine the stress at which the increase in length begins to be out of proportion to the increase in load requires careful

and accurate measurement. Under a somewhat higher stress, the sudden change in length is easily observed, and this stress, called the "yield point," is, therefore, commonly assumed to produce the first permanent set. The distinction should be noted. Here the bar may continue to stretch without an increase in load, and the yield point then be determined by a drop of the weighing beam. Under some conditions, particularly with alloy steels, this drop does not occur, but the sudden increase in length can be observed with a pair of dividers, the legs being placed in the marks that indicate the standard length. Testing machines are usually equipped with a curve-drawing device by which the yield point and elastic limit can be determined by the change in direction of the curve. Tensile strength and elastic limit, or yield point, are reported in pounds per square inch.

The length after fracture is measured after the broken ends are fitted together, and the increase is reported as a percentage of the original length, which is also given. This increase in length is known as the "elongation." The elongation varies with the original length of the test bar, and a standard length is necessary. Standard lengths are 2, 4, 8 in., but for the common machined cylindrical test bar the standard length is 2 in. and is marked with a prick punch. If, at fracture, the length between the marks has increased to 3 from 2 in., the elongation is 50 per cent in 2 in.

This increase in length is paralleled by a decrease in the cross-sectional area particularly noticeable at the fracture where a *necking-in* occurs. The area at the fracture is measured and deducted from the original area, the remainder being the reduction of area reported in percentage. Elongation and reduction of area indicate ductility and are closely related, although one is not always exactly dependent upon the other.

Torsional Properties.—Corresponding properties are also determined by torsional test (twisting), the elastic limit in torsion being the stress at which a permanent set is first obtained, and the stress required to break is called the "torsional strength." Both are reported in inch-pounds based upon the load and the length of the lever arm. Ductility is determined by the angle of twist after fracture, reported in degrees. The resistance to compression may also be determined. Properties in torsion and compression bear a close relationship to properties in tension,

and in practice tensile properties are the general standard of comparison.

The Elasticity of Steel. Modulus of Elasticity.—Steel, like many other materials, is elastic, which means that stress will produce deformation or change of shape but that the original form will be regained when the stress is removed, provided that the elastic limit is not exceeded. The temporary change of shape, or strain, is proportional to the stress. Elasticity is measured by dividing unit stress by the resulting unit strain. For example, a bar 2 in. long and 1 sq. in. in cross-sectional area under a pull of 30,000 lb. stretches 0.002 in. The strain per unit length, 1 in., is 0.001 in., the unit stress is 30,000 lb. per square inch. Dividing as stated, a factor of 30,000,000 is obtained, the modulus of elasticity. Regardless of composition, condition, and treatment, the modulus of elasticity is practically the same for all steels, varying from 28,000,000 to 31,000,000, approximately, or, more commonly, from 29,000,000 to 30,000,000, the last figure being generally employed. Elasticity is sometimes an important factor in design.

Hardness Tests, Brinell, Scleroscope, Rockwell Hardness.—In practice, tensile, or corresponding, tests are not serviceable for inspection because of the time required, the expense, and the destruction of the test bar or piece but supply a standard for hardness tests that can be used for inspection. Several types of hardness-testing machines have been devised, but only three tests are at present standard in industrial practice, the Brinell, the scleroscope (or Shore), and the Rockwell. These tests will be described in the chapter on inspection, but all are based upon the same general principle and are indicative of the tensile strength. Brinell hardness is measured by the diameter of the impression made by a ball of standard size under a standard load. Hardness may be reported in terms of the diameter of the impression, for example 3.0 mm., but is usually reported by Brinell hardness numbers which are calculated by a formula from the diameter measured. For 3.0 mm., the corresponding Brinell hardness number is 418. The approximate range of Brinell hardness for steel, from the softest to the hardest, lies between 100 and 600. Beyond 500, however, accurate measurement becomes increasingly difficult.

The scleroscope measures hardness by the rebound of a diamond-pointed hammer dropped from a fixed height. Equal

divisions are marked off on a vertical scale from zero at the bottom to 140 (120 is sometimes the maximum) at the top. The reading is made directly with one type of scleroscope but is recorded on a dial by another type. The approximate range of scleroscope (sometimes called Shore) hardness lies between 20 and 110.

Rockwell hardness is determined by the depth of the impression made by a diamond point or by a steel ball under a standard

General Relationship of Brinell, Rockwell, Scleroscope Hardness, and Tensile Strength

Brinell		Rockwell C scale	Shore hardness	Tensile strength, thousands of pounds	Brinell		Rockwell C scale	Shore hardness	Tensile strength, thousands of pounds
Diam. of impression, millimeters	Hardness number for 3,000 kg.				Diam. of impression millimeters	Hardness number for 3,000 kg.			
2.50	601	59	83	.....	4.20	207	18.5	33	101.8
2.55	578	57.5	81	.....	4.25	201	17	31	98.9
2.60	555	56	78	.....	4.30	197	15	30+	96.9
2.65	534	54.5	76	.....	4.35	192	13.5	30−	94.5
2.70	514	53	73	.....	4.40	187	12.0	29−	92.0
2.75	495	51.5	71	243.5	4.45	183	11.0	28.5	90.0
2.80	477	50	69	234.7	4.50	179	9.5	28	88.1
2.85	461	49	67	226.8	4.55	174	7.5	27	85.6
2.90	444	48	65	218.4	4.60	170	6	26.5	83.6
2.95	429	47	64	211.1	4.65	167	4.5	26+	82.2
3.00	415	45.5	62	204.2	4.70	163	3	26−	80.2
3.05	401	44	60	197.3	4.75	159	1	25.5	78.2
3.10	388	43	58	190.9	4.80	156	0	25	76.8
3.15	375	42	57	184.5	4.85	152	−2	....	74.8
3.20	363	41	56	178.6	4.90	149	−3	....	73.3
3.25	352	40	54	173.2	4.95	146	−5	....	71.8
3.30	341	39	53	167.8	5.00	143	−6.5	....	70.4
3.35	331	38	52	162.9	5.05	140	....	....	68.9
3.40	321	37	50	157.9	5.10	137	....	....	67.4
3.45	311	36	49	153.0	5.15	134	....	....	65.9
3.50	302	35	48	148.6	5.20	131	....	....	64.5
3.55	293	34	47	144.2	5.25	128	....	....	63.0
3.60	285	33	46	140.2	5.30	126	....	....	62.0
3.65	277	32	45	136.3	5.35	123	....	....	60.5
3.70	269	31	44	132.3	5.40	121	....	....	59.5
3.75	262	30	42	128.9	5.45	118	....	....	58.1
3.80	255	29	41	125.5	5.50	116	....	....	57.1
3.85	248	27.5	40	122.0	5.55	114	....	....	56.1
3.90	241	26	39	118.6	5.60	111	....	....	54.6
3.95	235	25	38	115.6	5.65	109	....	....	53.6
4.00	229	24	37	112.7	5.70	107	....	....	52.6
4.05	223	22.5	36	109.7	5.75	105	....	....	51.7
4.10	217	21	35	106.8	5.80	103	....	....	50.7
4.15	212	20	34	104.3	5.85	101	....	....	49.7

Brinell values from *Bur. Standards Misc. Pub.* 62; tensile strength = 492 × Brinell hardness number.

load and is registered on a direct-reading dial. Two scales are provided, one for each type of penetrator, lettered, respectively, *B* for the ball and *C* for the diamond penetrator. The maximum Rockwell hardness of steel may be considered as 60 on the *C* scale, although a slightly greater hardness has been obtained with special steels. The hardness of soft steel is below zero on the *C* scale and is, therefore, measured on the *B* scale with the ball penetrator.

These hardness tests supplement the tensile test or may be used when a tensile test is impossible. They are intended primarily for inspection, are used as a check upon production, and will, therefore, be considered in more detail in the chapter dealing with inspection methods. Hardness tests are checked by the tensile test, hardness numbers being related to the tensile strength. The table on page 52 shows the general relationship between the various hardness numbers and the tensile strength. This table is by no means accurate for all purposes. Wide variations occur in practice largely because steel is not always uniform throughout. Furthermore, the relationship between hardness and tensile strength varies somewhat with different types of steel, particularly in the higher ranges.

Dynamic Tests.—The tests described are static, and the results are of service in determining the resistance of steel to static loads. Materials in service, however, may also be required to resist dynamic stress, shock, blows, and rapid alternating stresses. Exact methods of testing to determine resistance to shock would be of great value to the engineer. Methods of testing have been developed that are of service for making comparisons, but none of these tells directly the results to be expected in service, because service stresses vary widely. The effect of shock can be measured comparatively by observing the effect of a falling weight dropped through a known distance, counting the number of blows required to fracture, a test that is known as the "drop test." A modification of this, the *impact test*, allows the weight to swing at the end of a bar, like a pendulum, and to strike a test piece placed at the bottom of the swing. Work is performed in breaking, and the amount is indicated by the rise of the weight after it has broken the test piece. Swinging free, the weight will rise practically as far as it has dropped, but if a test piece is introduced, the rise will be checked. The more brittle the piece the less will be the work required to break

it and the less hindrance to the falling weight. The higher it rises the more brittle the steel.

The impact test, made with a notched bar, has no practical value, unless comparative, and will frequently give misleading results. It is mentioned because of references in the literature, particularly foreign, but has not been extensively adopted in this country and should be omitted from general tests.

Tensile Properties as a Standard.—The tensile properties, tensile strength, elastic limit, or yield point, elongation, reduction of area, and, also, the hardness numbers are far more convenient for describing condition and more accurate than the vague terms such as "hard," "tough," and others of the same character heretofore used. They are, therefore, convenient for describing the results of heat treatment by which a range of properties can be obtained. The effect of tempering, after hardening, in reducing the tensile strength and increasing the ductility progressively with rise in temperature can be plotted. Charts showing the effect of varying the drawing temperature are known as "physical-property charts."

The tensile properties offer a convenient standard by which condition may be determined, the results of differences in composition and heat treatment may be compared, and the application of materials in service may be guided. Tensile tests, however, and other static tests as well, do not always present a perfect picture of physical condition. The results will vary under apparently similar conditions, perhaps because of differences in structure, grain size, and other conditions not easily observed. Static tests may give some indication of the resistance of a material to dynamic stresses in service, but not always. They can at best only approximate and cannot duplicate the conditions of stress met in service and must, therefore, be used with discretion. The tensile test can, however, present a reasonably good picture of the ability of a material to resist static and even dynamic loads, at least by comparison, and will serve as a guide in steel treating.

Marked differences in properties are brought out by the tensile test. For example, compare the results obtained with tests of samples *A*, *B*, and *C*, shown in Table I.

A is hard and brittle, the ductility being low; *B* is harder but not so brittle, the ductility being higher; *C* is comparatively soft and very ductile. To these samples further reference will be made.

TABLE I

	A	B	C
Yield point	160,000	222,000	90,000
Tensile strength	210,000	265,000	110,000
Elongation in 2 in., per cent	2	8	22.5
Reduction of area, per cent	3	27	66
Brinell hardness	401	495	201

Physical Property Heat-treatment Charts.—Physical-property charts are convenient for comparing the properties that can be obtained with different types of steel as well as for determining the effect of drawing at different temperatures. A large number of such charts is necessary to cover all types of steel. Physical-property charts for various types of steel intended to cover the commercial range of carbon have been published. Unfortunately, physical tests do not always agree even with the same type of steel, and even greater disagreement is to be expected in attempting to give representative physical properties for commercial ranges of carbon. Physical properties may differ in steels that are alike except for a difference in grain size. Banding, a common condition, also affects the results obtained. Variation from typical charts must be expected, therefore. The individual user of steel must work out his own charts and select drawing temperatures in accordance with the results of his own tests and for the particular properties desired. He seldom requires information regarding the properties obtained throughout the entire drawing range. Usually, all that is necessary is a knowledge of the drawing temperature required to obtain a specified Brinell, or other form of hardness.

The literature of steel treating is somewhat vague in dealing with the physical properties obtained with different types of steel, probably because of the difficulty of obtaining a general agreement. Many results have been published, but these are often incomplete. Material from one source differs from material from another source, and many writers, therefore, take refuge in general terms such as "hardness" and "toughness." The properties obtained by steel treating, however, are best described by some reference to tensile properties, and selected results and charts will, therefore, be given not for use but merely for illustration. This will permit a general comparison.

Selection has been made from several reliable sources. Charts presenting average properties for a range of ten points of carbon have been included, but preference has been given to charts based upon exact composition, because they are more accurate and provide a better basis for comparison.

Effect of "Mass."—The physical properties obtained by heat treating steel vary with the thickness or diameter of the piece treated, all other conditions being the same. This effect is sometimes called the "effect of mass," but the term " mass" is misleading in that it generally refers to total volume or total weight. Mass, in the sense of total volume or weight, may have some effect if the piece is very large or of irregular section, but difference in physical properties depends more upon one dimension, and that the smallest. With this distinction, however, the term "mass" will be employed for convenience. Because of this effect, the diameter, or other important dimension, of the piece treated will be given in connection with physical-property charts and tables presented here.

S. A. E. and Other Physical-property Charts.—Table II presents a few physical-property charts made by the Society of Automotive Engineers and includes some that illustrate the effect of mass. Charts from other sources are shown in Table III for comparison, of which four represent average properties for a ten-point range of carbon. The other charts are selected from tests of steels of specified composition, the figures representing the average condition rather than an average of a number of tests, although averages of tests have been included. The difference in the results is apparent. Some difference is due to variation in the size of the sample treated, some to the selection of different minimum figures, and some to the differences in condition that occur in steel.

Applying Physical-property Charts to Practice.—The results of tensile tests often differ even with samples taken from the same bar, and different heats of steel usually have different physical properties, although the difference may be comparatively slight. Physical properties better than the average can be obtained from selected heats. Physical-property charts should, therefore, be used only for general comparison, and charts based upon a range of carbon should be used with caution, if at all. The method of taking the average should be known. Charts based upon definite composition and upon a particular carbon content

TABLE II.—CHART FOR S. A. E. STEEL 1035

QUENCHED IN WATER

CHEMICAL COMPOSITION IN PERCENTAGE

Carbon	0.30–0.40
Manganese	0.50–0.80
Phosphorus	0.045 max.
Sulphur	0.055 max.

Quenched at 1525 to 1575 deg. fahr. in *water*.

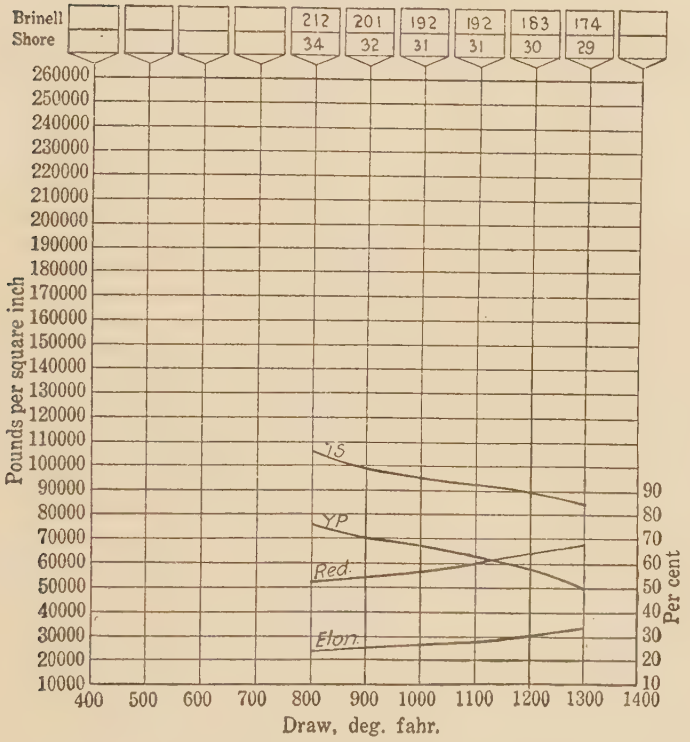


TABLE II (*Continued*).—CHART FOR S. A. E. STEEL 1045

QUENCHED IN WATER

CHEMICAL COMPOSITION IN PERCENTAGE

Carbon	0.40–0.50
Manganese	0.50–0.80
Phosphorus	0.045 max.
Sulphur	0.055 max.

Quenched at 1475 to 1525 deg. fahr. in *water*.

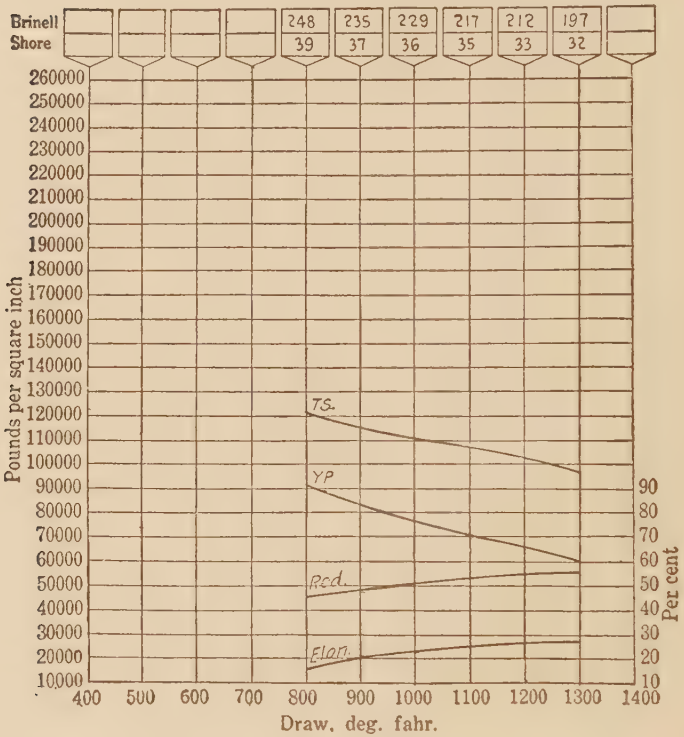


TABLE II (*Continued*).—CHART FOR S. A. E. STEEL 1045

QUENCHED IN OIL

CHEMICAL COMPOSITION IN PERCENTAGE

Carbon	0.40–0.50
Manganese	0.50–0.80
Phosphorus	0.045 max.
Sulphur	0.055 max.

Quenched at 1475 to 1525 deg. fahr. in *oil*.

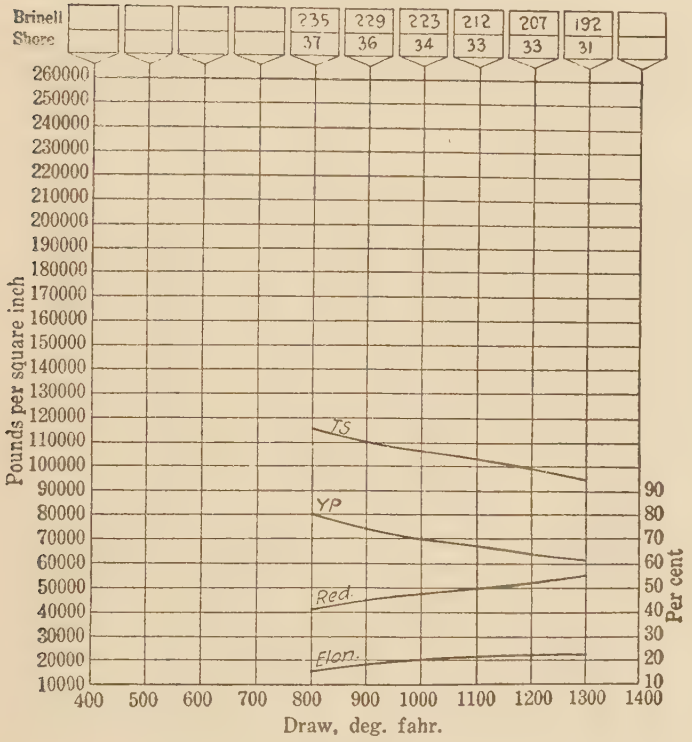


TABLE II (*Continued*).—CHART FOR S. A. E. STEEL 3130

QUENCHED IN OIL

CHEMICAL COMPOSITION IN PERCENTAGE

Carbon	0.25–0.35
Manganese	0.50–0.80
Phosphorus	0.04 max.
Sulphur	0.05 max.
Nickel	1.00–1.50
Chromium	0.45–0.75

Normalized at 1650 to 1750 deg. fahr.
Quenched at 1500 to 1550 deg. fahr. in *oil*.

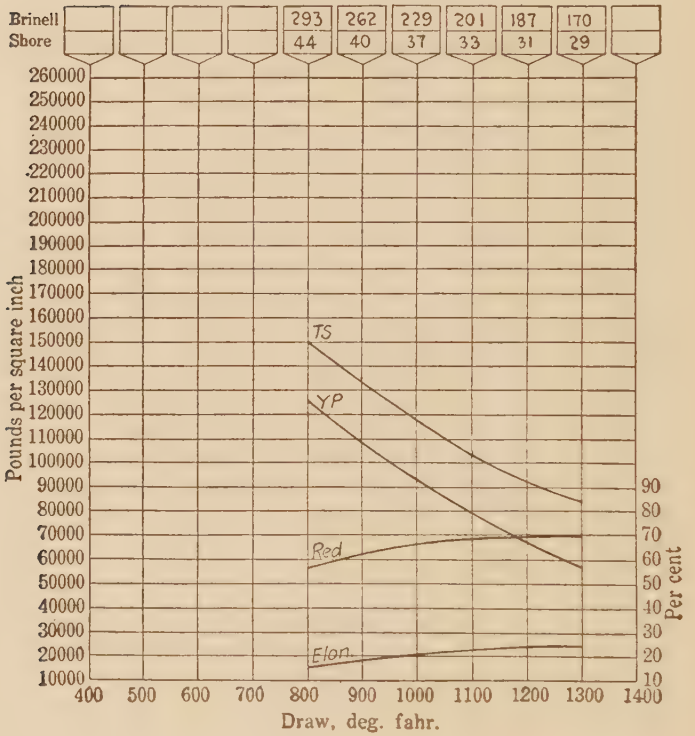


TABLE II (*Continued*).—CHART FOR S. A. E. STEEL 3130

QUENCHED IN WATER

CHEMICAL COMPOSITION IN PERCENTAGE

Carbon	0.25–0.35
Manganese	0.50–0.80
Phosphorus	0.04 max.
Sulphur	0.05 max
Nickel	1.00–1.50
Chromium	0.45–0.75

Normalized at 1650 to 1750 deg. fahr.
Quenched at 1500 to 1550 deg. fahr. in *water*.

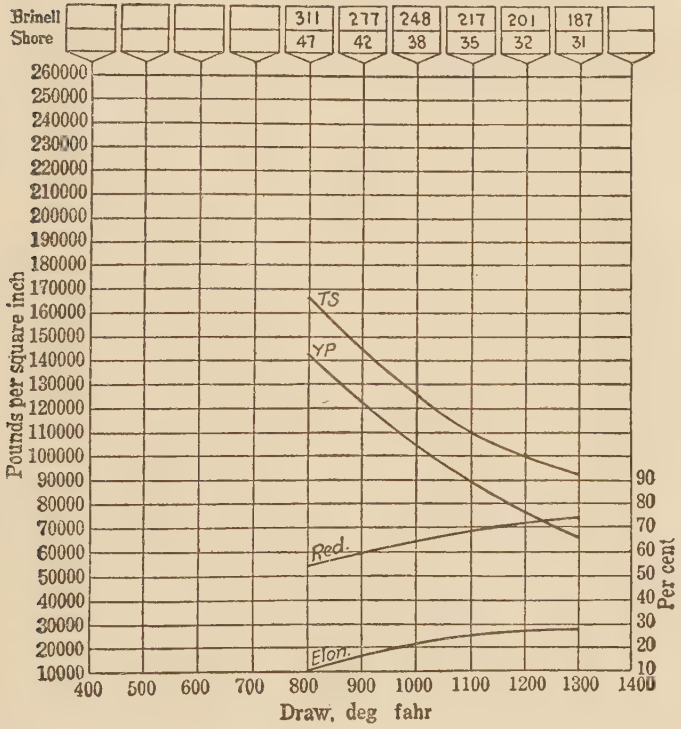


TABLE II (*Continued*).—CHART FOR S. A. E. STEEL 3140

CHEMICAL COMPOSITION IN PERCENTAGE

Carbon	0.35–0.45
Manganese	0.50–0.80
Phosphorus	0.04 max.
Sulphur	0.05 max.
Nickel	1.00–1.50
Chromium	0.45–0.75

Normalized at 1600 to 1700 deg. fahr.
Quenched at 1475 to 1525 deg. fahr. in *oil*.

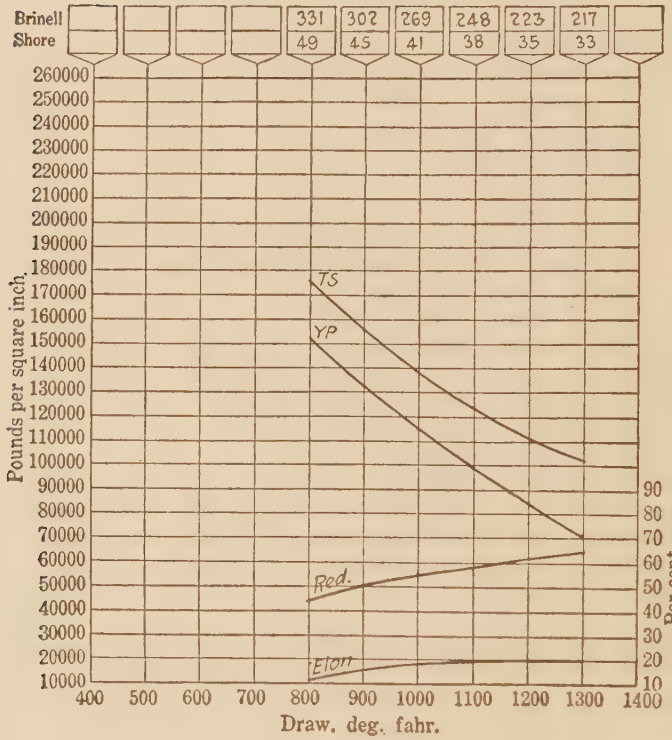


TABLE II (*Continued*).—CHART FOR S. A. E. STEEL 2340

CHEMICAL COMPOSITION IN PERCENTAGE

Carbon	0.35–0.45
Manganese	0.50–0.80
Phosphorus	0.04 max.
Sulphur	0.05 max.
Nickel	3.25–3.75

Normalized at 1625 to 1725 deg. fahr.
Quenched at 1425 to 1475 deg. fahr. in *oil*.

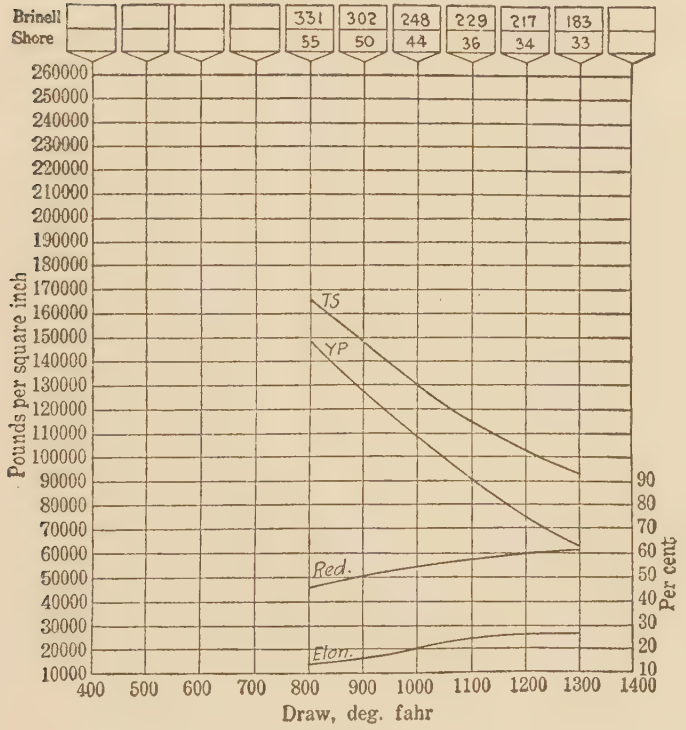
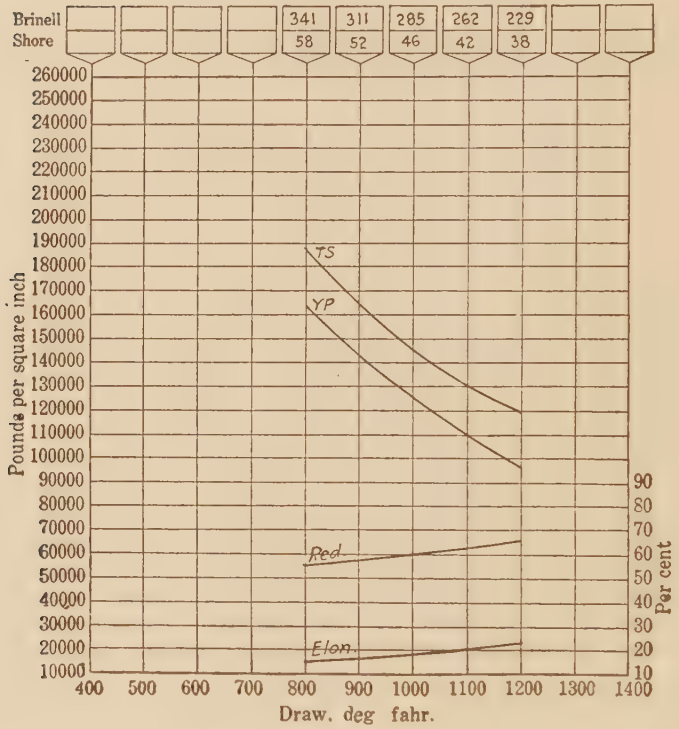


TABLE II (*Continued*).—CHART FOR S. A. E. STEEL 3435

CHEMICAL COMPOSITION IN PERCENTAGE

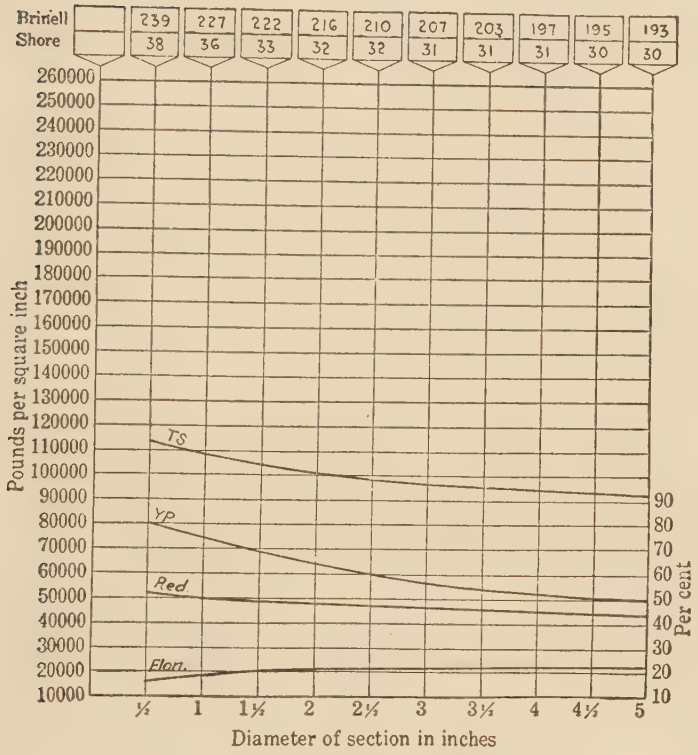
Carbon	0.30–0.40
Manganese	0.30–0.60
Phosphorus	0.04 max.
Sulphur	0.045 max.
Nickel	2.75–3.25
Chromium	0.60–0.95

Normalized at 1550 to 1650 deg. fahr.
Quenched at 1425 to 1475 deg. fahr. in *oil*.



EFFECT OF MASS

TABLE II (*Continued*).—CHART FOR S. A. E. STEEL 1045 QUENCHED AT 1500 DEG. FAHR. IN OIL AND DRAWN AT 1000 DEG. FAHR.



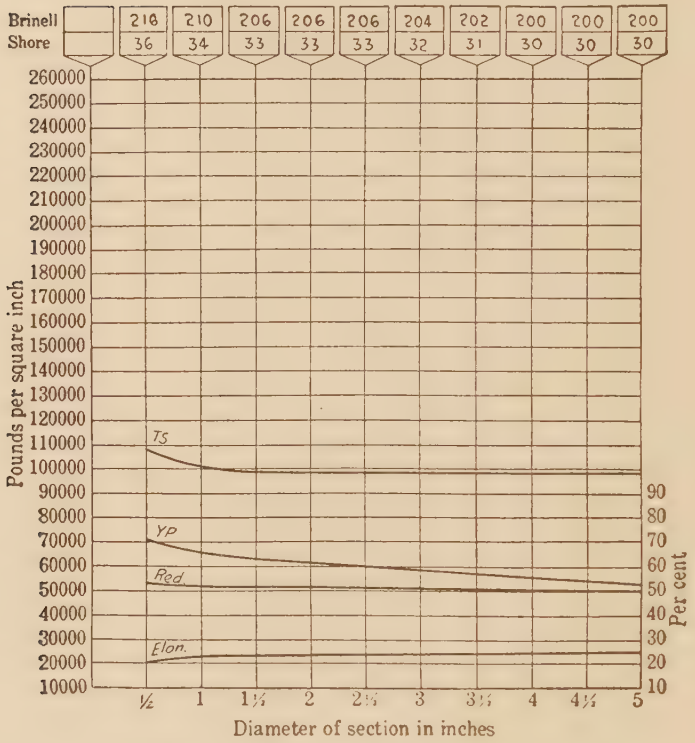
CHEMICAL COMPOSITION IN PERCENTAGE

Carbon	0.40–0.50
Manganese	0.50–0.80
Phosphorus	0.045 max.
Sulphur	0.055 max.

EFFECT OF MASS

TABLE II (*Continued*).—CHART FOR S. A. E. STEEL 1045

QUENCHED AT 1500 DEG. FAHR. IN OIL AND DRAWN AT 1200 DEG. FAHR.

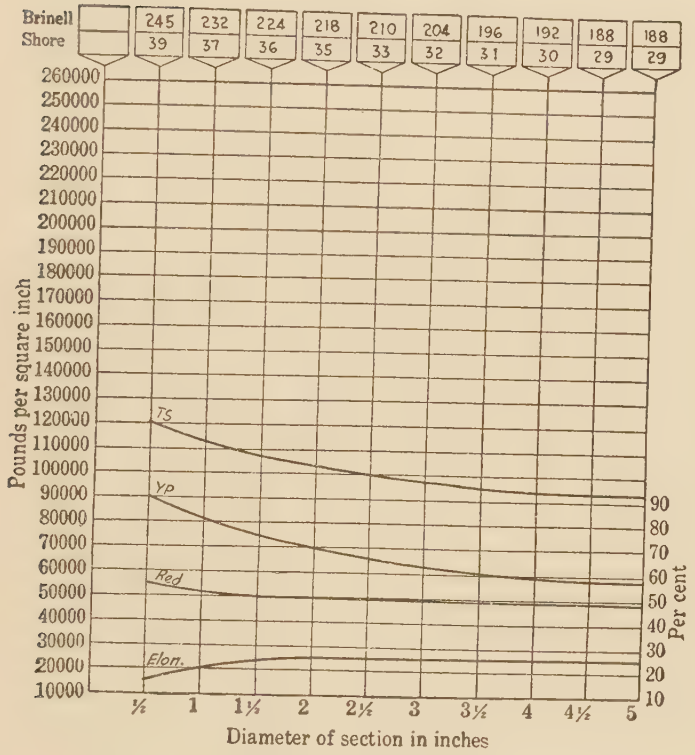


CHEMICAL COMPOSITION IN PERCENTAGE

Carbon	0.40–0.50
Manganese	0.50–0.80
Phosphorus	0.045 max.
Sulphur	0.055 max.

EFFECT OF MASS

TABLE II (*Continued*).—CHART FOR S. A. E. STEEL 1045 QUENCHED AT 1500 DEG. FAHR. IN WATER AND DRAWN AT 1000 DEG. FAHR.



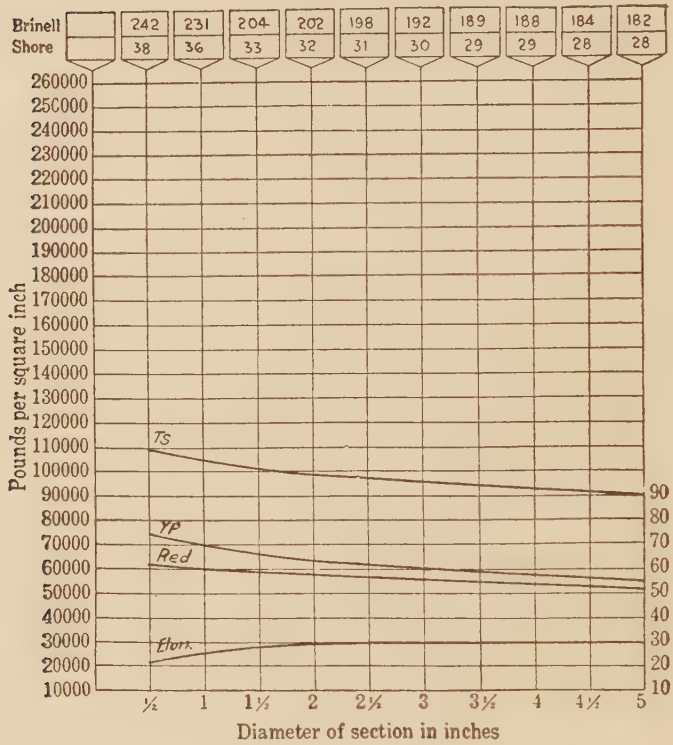
CHEMICAL COMPOSITION IN PERCENTAGE

Carbon	0.40–0.50
Manganese	0.50–0.80
Phosphorus	0.045 max.
Sulphur	0.055 max.

EFFECT OF MASS

TABLE II (*Continued*).—CHART FOR S. A. E. STEEL 1045

QUENCHED AT 1500 DEG. FAHR. IN WATER AND DRAWN AT 1200 DEG. FAHR.



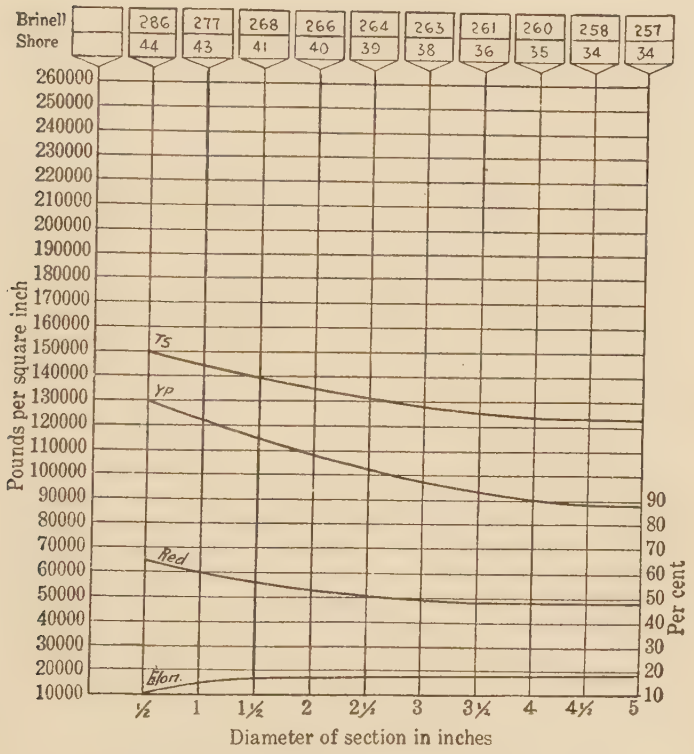
CHEMICAL COMPOSITION IN PERCENTAGE

Carbon	0.40–0.50
Manganese	0.50–0.80
Phosphorus	0.045 max.
Sulphur	0.055 max.

EFFECT OF MASS

TABLE II (*Continued*).—CHART FOR S. A. E. STEEL 3140

NORMALIZED AT 1600 TO 1700 DEG. FAHR., QUENCHED AT 1500 DEG. FAHR. IN OIL AND DRAWN AT 1000 DEG. FAHR.



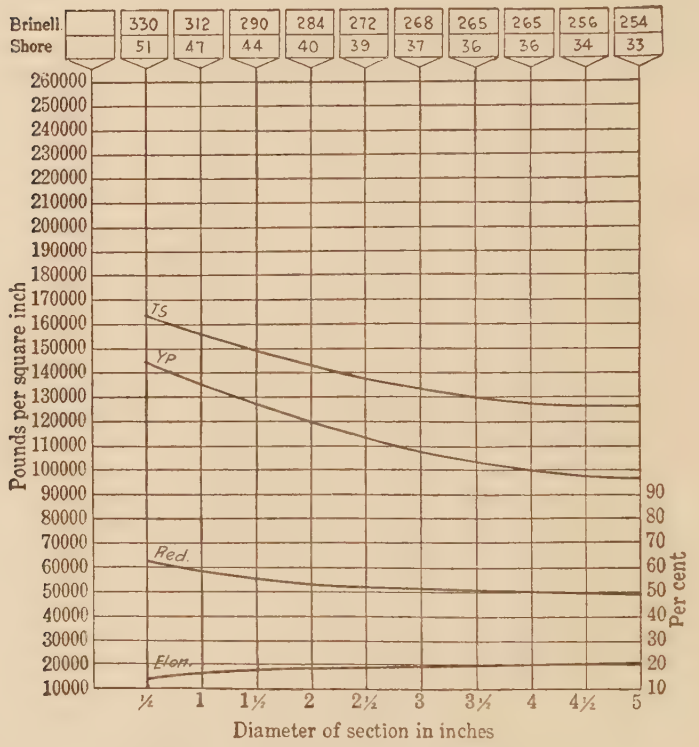
CHEMICAL COMPOSITION IN PERCENTAGE

Carbon	0.35–0.45
Manganese	0.50–0.80
Phosphorus	0.04 max.
Sulphur	0.05 max.
Nickel	1.00–1.50
Chromium	0.45–0.75

EFFECT OF MASS

TABLE II (*Continued*).—CHART FOR S. A. E. STEEL 3140

NORMALIZED AT 1600 TO 1700 DEG. FAHR., QUENCHED AT 1500 DEG. FAHR. IN WATER AND DRAWN AT 1000 DEG. FAHR.



CHEMICAL COMPOSITION IN PERCENTAGE

Carbon	0.35–0.45
Manganese	0.50–0.80
Phosphorus	0.04 max.
Sulphur	0.05 max.
Nickel	1.00–1.50
Chromium	0.45–0.75

TABLE III.—CHART FOR 1085 TYPE

	Per Cent
Carbon	0.84
Manganese	0.67

Oil Quenched from 1400° F.
Size: 1″ RD

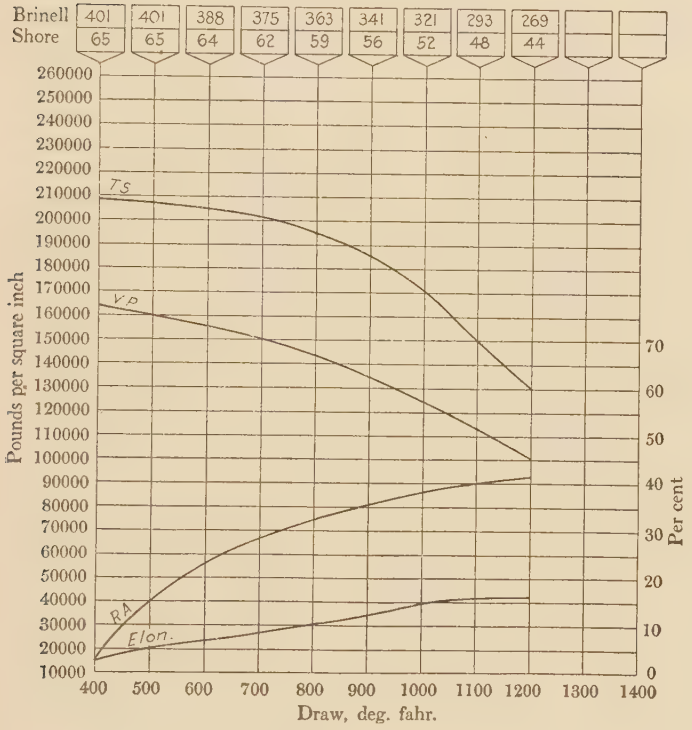


TABLE III (*Continued*).—CHART FOR 1335 TYPE

	Per Cent
Carbon	0.32
Manganese	1.36

Water Quenched from 1560° F.
Size: 1″ RD

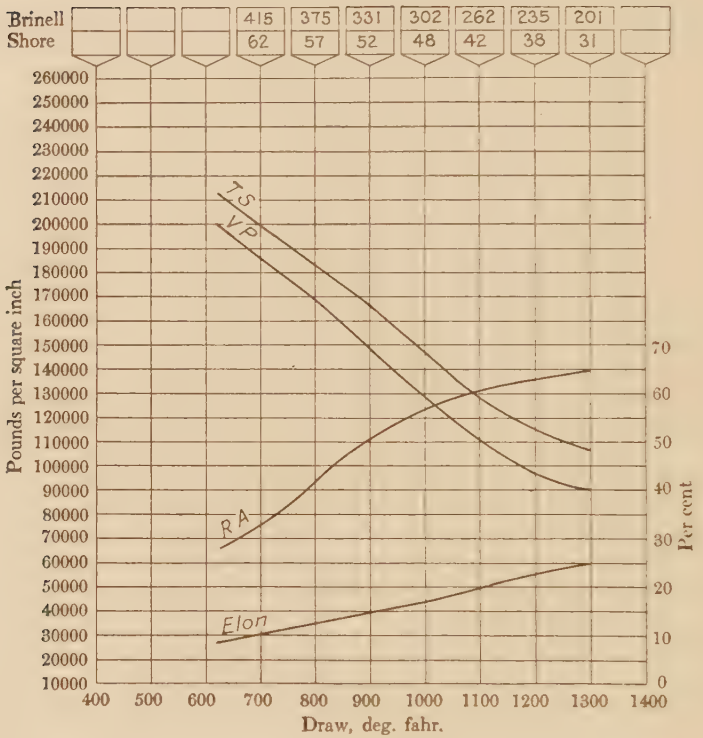


TABLE III (*Continued*).—CHART FOR 2335–2340 TYPE

	Per Cent
Carbon	0.37
Manganese	0.65
Nickel	3.50

Oil Quenched from 1400° F.
Size: 1″ Rd.

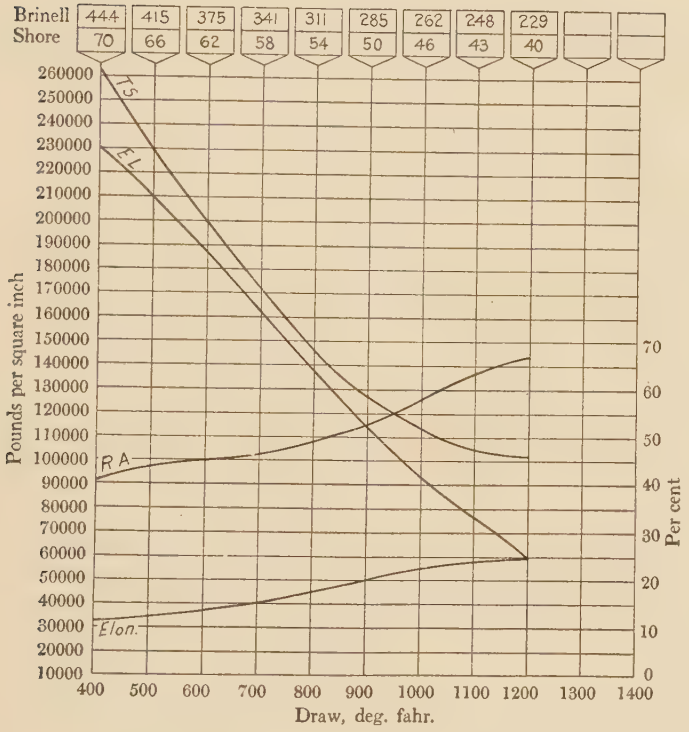


TABLE III (*Continued*).—CHART FOR 2350 TYPE

	Per Cent
Carbon	0.50
Manganese	0.55
Nickel	3.40

Oil Quenched from 1375° F.
Size: 1″ Rd.

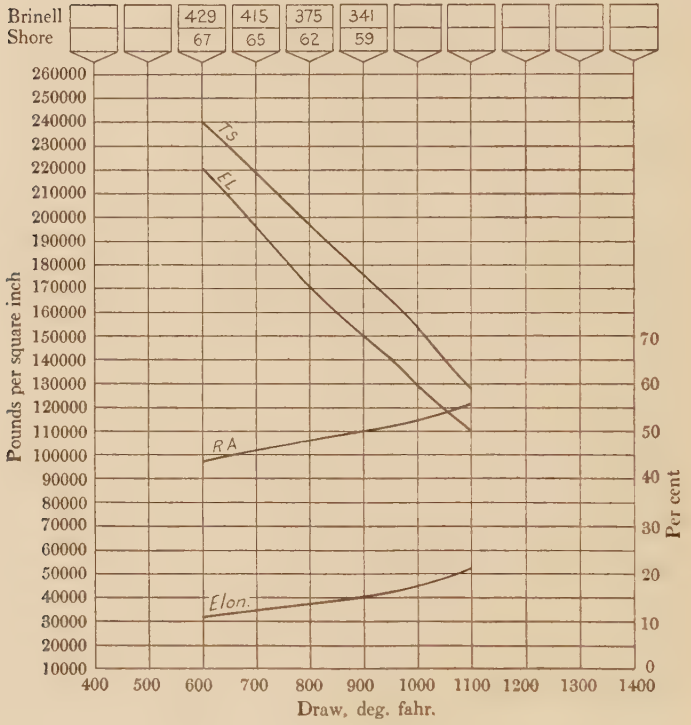


TABLE III (*Continued*).—CHART FOR 3135 STEEL

	Per Cent
Carbon	0.30–0.40
Manganese	0.50–0.70
Nickel	1.00–1.50
Chromium	0.45–0.75

Oil Quenched from 1500°–1530° F.
Size: ½″–1½″ Rd.

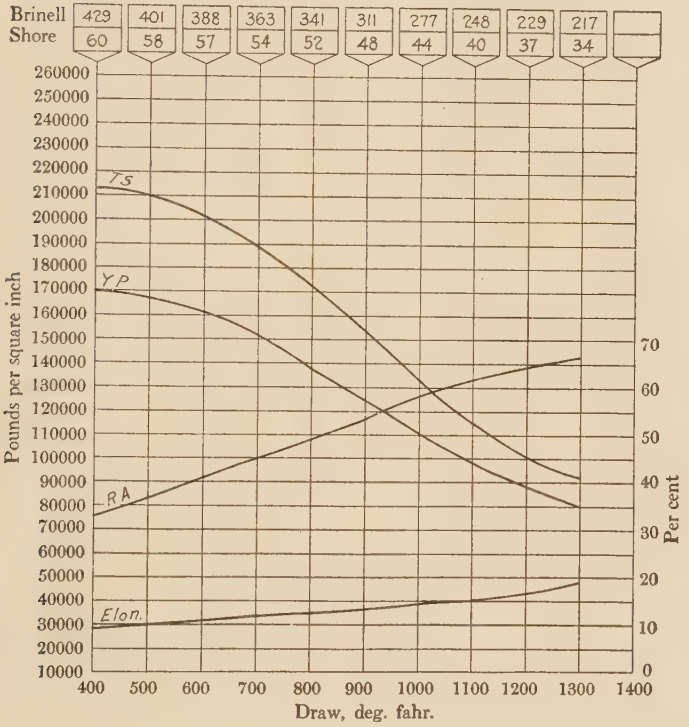


TABLE III (*Continued*).—CHART FOR 3145 STEEL

	Per Cent
Carbon	0.40–0.50
Manganese	0.50–0.70
Nickel	1.00–1.50
Chromium	0.45–0.75

Oil Quenched from 1485°–1515° F.
Size: ½″–1½″ Rd.

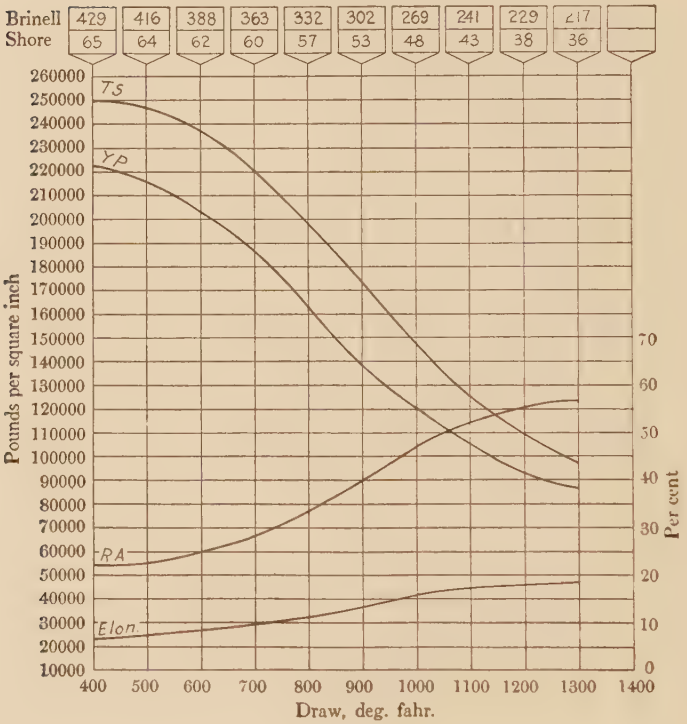


TABLE III (*Continued*).—CHART FOR 3135–3140 TYPE

	Per Cent
Carbon	0.37
Manganese	0.55
Nickel	1.35
Chromium	0.45

Oil Quenched from 1450° F.
Size: 1″ Rd.

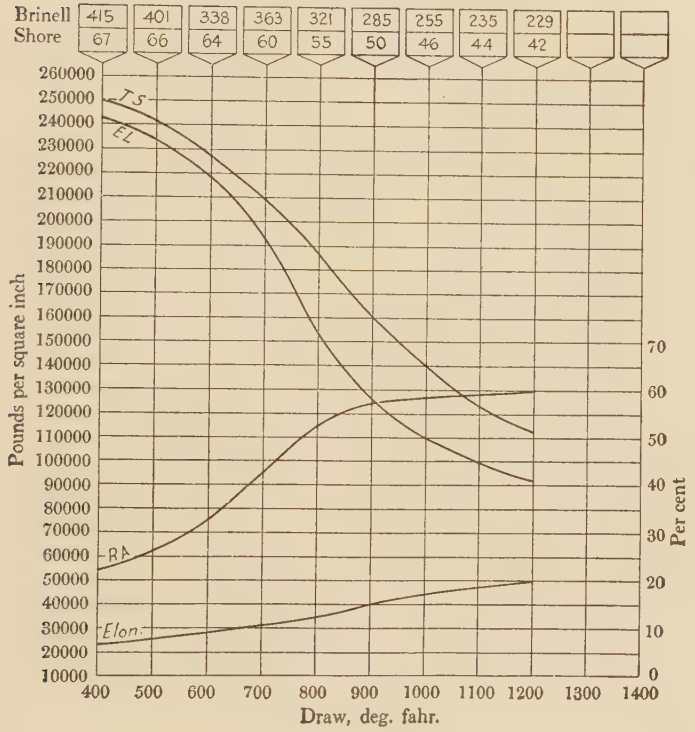


TABLE III (*Continued*).—CHART FOR 3245 TYPE

	Per Cent
Carbon	0.45
Manganese	0.45
Nickel	1.75
Chromium	1.00

Oil Quenched from 1425° F.
Size: 1″ Rd.

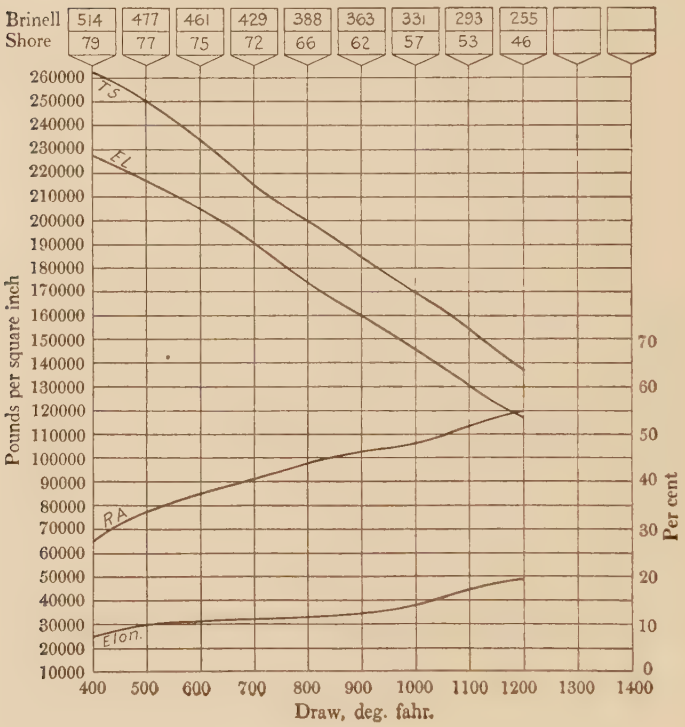


TABLE III (*Continued*).—CHART FOR 3250 STEEL

	Per Cent
Carbon	0.45–0.55
Manganese	0.30–0.50
Nickel	1.50–2.00
Chromium	0.90–1.20

Oil Quenched from 1450° F.
Size: ½″–1½″ Rd.

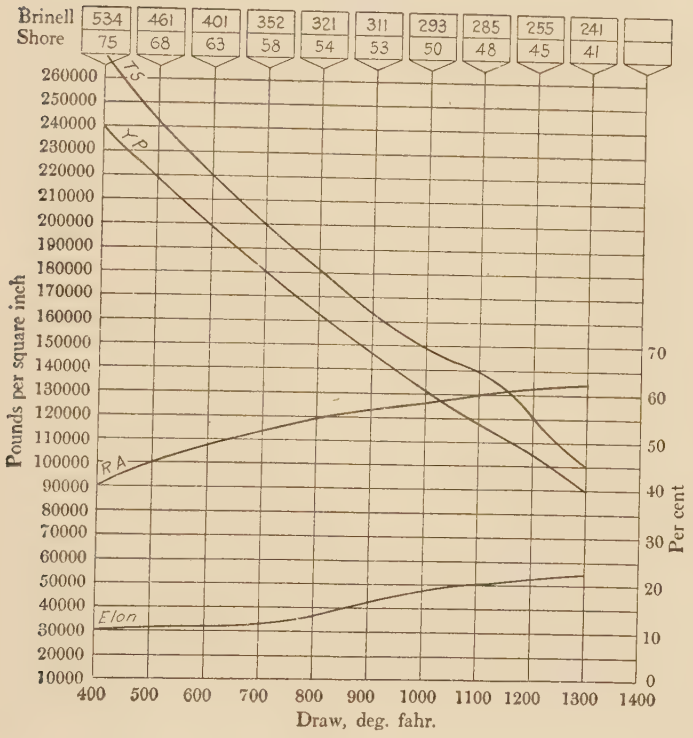


TABLE III (*Continued*).—CHART FOR 3340 TYPE

	Per Cent
Carbon	0.40
Manganese	0.41
Nickel	3.50
Chromium	1.50

Oil Quenched from 1400° F.
Size: 1″ Rd.

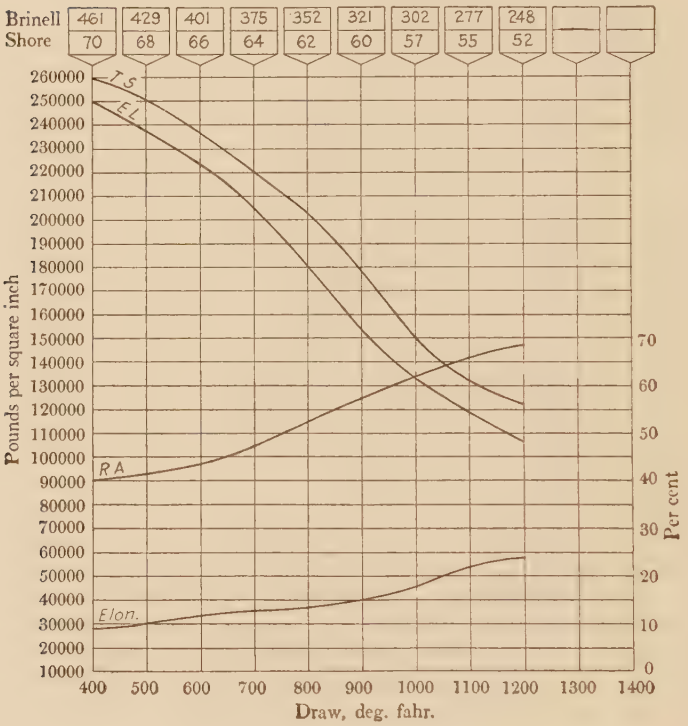


TABLE III (*Continued*).—CHART FOR 3430 TYPE

	Per Cent
Carbon	0.30
Manganese	0.60
Chromium	0.75
Nickel	3.02

Oil Quenched from 1425° F.
Size: 1″ Rd.

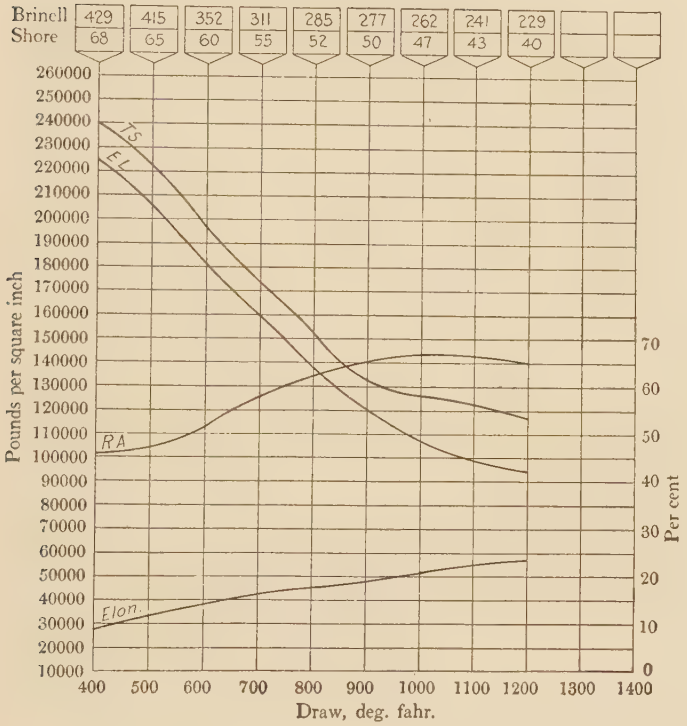


TABLE III (*Continued*).—CHART FOR 5150 STEEL

	Per Cent
Carbon	0.45–0.55
Manganese	0.60–0.80
Chromium	0.85–1.10

Oil Quenched from 1460°–1480° F.
Size: ½″–1½″ Rd.

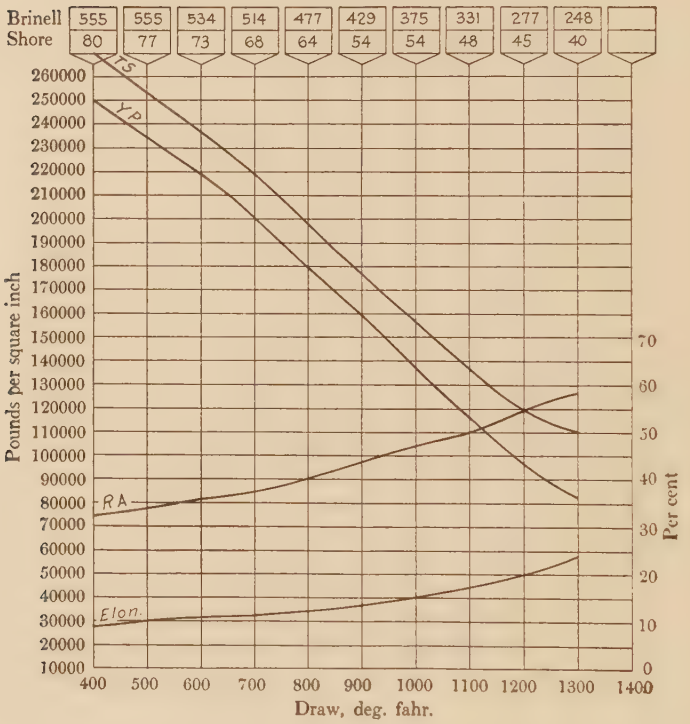
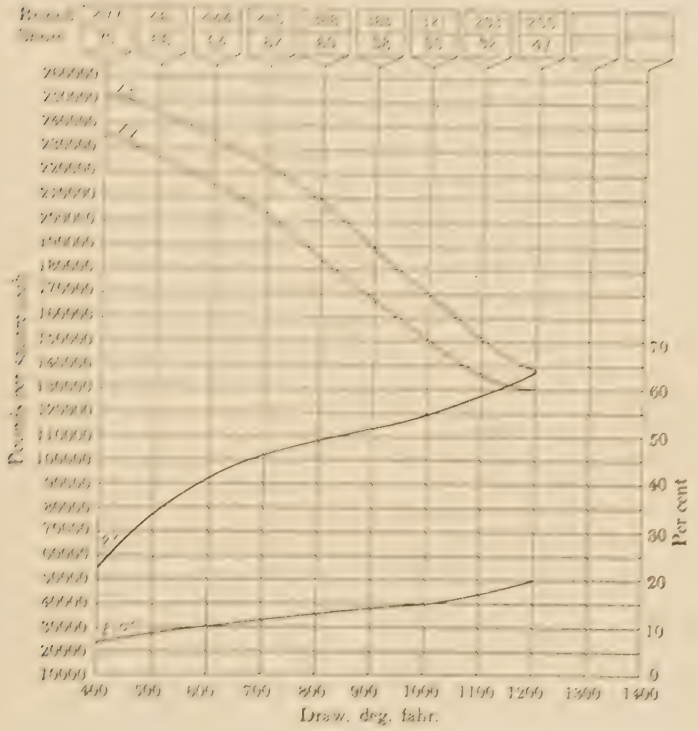


TABLE III (*Continued*).—CHART FOR 6140 TYPE

	Per Cent.
Carbon	0.40
Manganese	0.60
Chromium	1.04
Vanadium	0.18

Oil Quenched from 1525° F.
Size: 1" Rd.



are more accurate than those covering a carbon range and are more satisfactory for comparison or for determining the proper drawing temperature for properties that may be desired. It has been suggested that areas rather than lines be used to chart the physical properties in diagrams that cover a range of carbon, thus avoiding misunderstanding, which is usually due to differences in selecting averages for carbon content. Physical-property charts for plain carbon steels of low and medium carbon have been omitted, but one for high-carbon steel has been included for purpose of comparison. Published charts for carbon steels are inaccurate; in fact, accuracy is difficult because of the effect of varying conditions. Physical properties of carbon steels are shown in the tables, however, the figures being taken from individual tests.

Comparison of Physical Properties.—The general effect of alloying elements can, perhaps, be better illustrated by comparison of individual physical properties in a table, but any effort in this direction faces the same difficulties. A general average is misleading, particularly with carbon steels. For convenience, however, a comparison has been made in Table IV with selected material. These figures, however, will not match results obtained under other conditions and, like the charts, are offered for illustration only. Some duplicates in composition are included to show variation in properties, and averages for a number of heats of one type are given as well as the results of individual tests. Some illustration of the effect of varying the quenching temperatures have been included. Selection has been made from types more commonly employed, from what might be called "medium-alloy" steels, of which the 1300, 3100, 6100 are representative. One example of a higher-alloy steel has been included, but others have been covered in the charts. To avoid the effect of variables as much as possible, so that a better comparison can be made, similarity in physical properties has been sought, but variations due to composition and treatment have been included.

TABLE IV.—REPRESENTATIVE RESULTS OF TENSILE TESTS

1015 type steel; carbon 0.15 per cent; manganese 0.30 per cent; quenched in water at 1675° F. and drawn as shown; bars 1½ in. diameter

Draw, degrees Fahrenheit	1,150	1,200	1,300
Yield point	42,500	43,000	42,500
Tensile strength	61,000	58,500	55,000
Elongation 2 in., per cent	38	41	42
Reduction of area, per cent	73	76	78

1025 type steel; carbon 0.26 per cent; manganese 0.38 per cent; quenched in water from 1650° F. and drawn as shown

Draw, degrees Fahrenheit	1,050	1,150	1,250	1,350
Yield point	54,000	50,500	48,500	45,500
Tensile strength	72,500	65,000	63,500	61,500
Elongation in 2 in., per cent	32	33	35	36
Reduction of area, per cent	60.5	65	69.5	69.5

1035 type steel; water quenched 1550° F.; drawn as shown; 1½ in. diameter treated; carbon 0.31 per cent

Draw, degrees Fahrenheit	1,000	1,090	1,100
Yield point	69,000	67,000	62,500
Tensile strength	92,000	94,000	90,000
Elongation 2 in., per cent	22	20	25
Reduction of area, per cent	52	52	67
Brinell hardness	183	192	167

1045 type steel; quenched and drawn as shown; 1½ in. diameter; carbon 0.38; manganese 0.61; water quenched from 1560° F.

Draw, degrees Fahrenheit	1,000	1,000	1,100	1,100
Yield point	74,000	68,500	69,000	64,000
Tensile strength	95,000	90,000	91,000	89,000
Elongation 2 in., per cent	20.5	23	22	24
Reduction of area, per cent	48	54	53	62

Water quenched from 1500–1525° F.; carbon 0.40; manganese 0.70

Draw, degrees Fahrenheit	800	900	1,000
Yield point	69,000*	83,000	75,000
Tensile strength	116,000	113,000	105,000
Elongation 2 in., per cent	19	20.5	23
Reduction of area, per cent	50.5	56	60
Brinell hardness	255	241	223

*Elastic limit

TABLE IV (*Continued*).—REPRESENTATIVE RESULTS OF TENSILE TESTS

Carbon 0.42; manganese 0.63

Draw, degrees Fahrenheit	700	800	900
Yield point	113,000	108,000	102,500
Tensile strength	151,000	145,000	138,500
Elongation 2 in., per cent	11.5	13.5	16
Reduction of area, per cent	31	36	42

Carbon 0.46; manganese 0.62

Draw, degrees Fahrenheit	700	800	900
Yield point	124,500	123,000	110,000
Tensile strength	161,000	159,000	149,000
Elongation 2 in., per cent	7	12.5	14.5
Reduction of area, per cent	17.5	35	41

Water quenched from 1500° F.; drawn 800° F.

Carbon	0.40	0.45	0.48
Elastic limit	69,000	78,000	91,000
Tensile strength	115,000*	129,000*	142,500*
Elongation 2 in., per cent	19	17.5	16
Reduction of area, per cent	50	47	43.5

NOTE.—The figures for carbon steels show variations that occur, but a fair average may be made from them.

3135 to 3140 type steel; water quenched from 1500° F.; drawn as shown; diameter 1⅜ in.; carbon 0.32; manganese 0.62; nickel 1.46; chromium 0.63

Draw, degrees Fahrenheit	900	1,000
Yield point	151,000	127,500
Tensile strength	164,000	141,500
Elongation 2 in., per cent	18	14.5
Reduction of area, per cent	51	54.5
Brinell hardness	364	321

Carbon 0.37, 0.36; manganese 0.60, 0.63; nickel 1.47, 1.46; chromium 0.60, 0.61; water quenched from 1500° F.

Draw, degrees Fahrenheit	950	950
Yield point	162,000	146,000
Tensile strength	171,000	153,500
Elongation 2 in., per cent	15	16
Reduction of area, per cent	53	55
Brinell hardness	331	341

TABLE IV (*Continued*).—REPRESENTATIVE RESULTS OF TENSILE TESTS

Carbon 0.43; manganese 0.59; nickel 1.35; chromium 0.64; water quenched from 1500° F.; drawn as shown 1⅜ in. diameter

Draw, degrees Fahrenheit	700	800	900
Yield point	220,000	211,000	168,000
Tensile strength	227,000	218,000	179,000
Elongation 2 in., per cent	9.5	12.5	14.5
Reduction of area, per cent	38	47	51

Carbon 0.43; manganese 0.63; nickel 1.33; chromium 0.67

Draw, degrees Fahrenheit	700	800	900
Yield point	223,000	206,000	166,500
Tensile strength	228,500	214,000	177,500
Elongation 2 in., per cent	10.5	12	14.5
Reduction of area, per cent	45	48.5	53.5

Carbon 0.43; manganese 0.69; nickel 1.35; chromium 0.60; oil quenched 1520° F.; drawn 450° F.; average analysis and results ten heats

Yield point	242,000
Tensile strength	282,000
Elongation 2 in., per cent	10
Reduction of area, per cent	29
Brinell hardness	534

2335 type steel; water quenched from 1450° F.; drawn as shown; 1⅜ in. diameter; carbon 0.35, 0.35, 0.34; manganese 0.81, 0.70, 0.55; nickel 3.32, 3.31, 3.47

Draw, degrees Fahrenheit	900	900	1,000
Yield point	153,000	157,000	115,000
Tensile strength	161,000	163,000	120,000
Elongation 2 in., per cent	16.5	16.5	22
Reduction of area, per cent	57	56	65
Brinell hardness	321	321	223

Carbon 0.37; manganese 0.50; nickel 3.66

Draw, degrees Fahrenheit	900	1,000
Yield point	148,500	127,000
Tensile strength	160,500	141,000
Elongation 2 in., per cent	14.5	18
Reduction of area, per cent	51	54.5
Brinell hardness	341	302

TABLE IV (*Continued*).—REPRESENTATIVE RESULTS OF TENSILE TESTS

Carbon 0.40; manganese 0.68; nickel 3.08

Draw, degrees Fahrenheit	700	800	900
Yield point	192,000	170,000	146,500
Tensile strength	205,000	187,000	156,500
Elongation 2 in., per cent	13	14.5	17.5
Reduction of area, per cent	51.4	54.5	58.5

Carbon 0.41; manganese 0.70; nickel 3.10

Draw, degrees Fahrenheit	700	800	900
Yield point	200,000	178,000	153,000
Tensile strength	210,000	192,500	161,500
Elongation 2 in., per cent	11.5	14.5	17.5
Reduction of area, per cent	49.5	51.5	56.5

ILLUSTRATING EFFECT OF VANADIUM

5140 type steel; water quenched from 1550° F.; carbon, 0.41; manganese, 0.51; chromium 0.82; vanadium none. 6140 type steel; water quenched from 1550° F.; carbon 0.41; manganese 0.79; chromium 0.93; vanadium 0.20

	5140 type		6140 type	
Draw, degrees Fahrenheit	900	1,000	900	1,000
Yield point	147,000	127,000	161,000	141,000
Tensile strength	159,000	141,000	175,000	154,000
Elongation 2 in., per cent	16.5	18	13	15.5
Reduction of area, per cent	44.5	51.5	48	54
Brinell hardness	364	311	375	341

3320 type steel; water quenched from 1500° F., drawn 900° F.; carbon 0.19, 0.19; manganese 0.58, 0.65; nickel 3.17, 3.13; chromium 1.07, 1.08

Yield point	151,000	151,000
Tensile strength	158,000	155,000
Elongation 2 in., per cent	17.5	17
Reduction of area, per cent	63	63.5
Brinell hardness	321	321

3335 type steel; average of 100 tests; 3 in. diameter; quenched 1500 to 1525° F. water; drawn 1100° F.

Yield point	128,500
Tensile strength	140,653
Elongation 2 in., per cent	17.8
Reduction of area, per cent	59.8
Brinell (head of test piece)	285

TABLE IV (*Continued*).—REPRESENTATIVE RESULTS OF TENSILE TESTS

3440 type steel; carbon 0.39; manganese 0.58; nickel 3.01; chromium 0.74; quenched 1450° F. water; drawn as shown; diameter 1⅜ in.

Draw, degrees Fahrenheit	900	1,000
Yield point	176,500	152,500
Tensile strength	185,500	162,500
Elongation 2 in., per cent	14.5	16.5
Reduction of area, per cent	51	53
Brinell hardness	388	341

1330 to 1335 type steel; carbon 0.31; manganese 1.49; water quenched from 1550° F., drawn as shown; 1⅜ in. diameter

Draw, degrees Fahrenheit	900	1,000
Yield point	121,000	112,000
Tensile strength	145,000	134,000
Elongation 2 in., per cent	15.5	17.5
Reduction of area, per cent	39	48.8
Brinell hardness	331	321

Carbon 0.37, 0.36; manganese 1.69, 1.72; 1550° F. water; drawn 950° F.

Yield point	146,000	141,000
Tensile strength	161,000	156,500
Elongation 2 in., per cent	14.5	14.5
Reduction of area, per cent	44.5	49
Brinell hardness	341	341

Carbon 0.27; manganese 1.51; 1550° F. water; drawn 900° F.

Yield point	105,000
Tensile strength	120,000
Elongation, per cent	24
Reduction of area, per cent	65

1300 type steel illustrating effect of molybdenum; quenched from 1550° F. in water; drawn 900° F.; carbon 0.29, 0.38; manganese 1.60, 1.76; molybdenum 0.23, 0.24

Yield point	143,000	170,500
Tensile strength	152,000	180,500
Elongation 2 in., per cent	19	16.5
Reduction of area, per cent	62.5	54

1350 type steel; oil quenched from 1450° F.; drawn at 450° F.; carbon 0.53, 0.48; manganese 1.67, 1.75; molybdenum none, 0.21

Yield point	250,000	240,000
Tensile strength	295,000	299,000
Elongation 2 in., per cent	9	12
Reduction of area, per cent	23	35

Physical Properties of Typical Steels.—The physical properties in Table IV have been selected as representative of the maximum requirements of average structural service, with drawing temperatures in the neighborhood of 900° F. (480° C.). Examples of the results of drawing at comparatively low temperature have been included to illustrate the maximum properties for tools and for compressive loads, but these examples indicate hardness somewhat high for average service. Table IV supplemented by reference to the charts of Table III, presents a general comparison of physical properties obtainable with different types of steel. In general, alloying elements increase the tensile strength and elastic limit, thus replacing carbon. This increased tensile strength may go beyond, and well beyond, the maximum obtainable with plain carbon steel. The ductility of alloy steel, furthermore, is superior to that of plain carbon steel of the same tensile strength.

The effect of the primary alloying elements, for example manganese, nickel, and chromium, is marked and, in general, depends upon the amount present. The results of combinations of nickel and chromium are superior to those obtained with either element alone. Combinations with the secondary alloying elements, vanadium and molybdenum, also improve properties, particularly the ductility, although the tensile strength may be somewhat increased, also. Steels containing large amounts of alloying elements singly or in combinations have not been included here, but the effect of these elements is still more marked. Of these, steels containing approximately 12 per cent of manganese, 12 per cent of chromium, or 14 per cent of tungsten as the basic alloying element are typical.

Selecting Steels for Service.—In structural service, the average requirements are met by steels of types represented by the 1300, 2300, 3100, 4100, 5100, and 6100 series. One type may be preferable to another for some specific purposes, for example, chromium steels for ball and roller bearings, but in average service these types are much alike, as the similarity in physical properties indicates. Choice will depend upon comparative cost, in which the expense of heat treating must be considered. Manganese being less costly than other alloying elements, the 1300 series, requiring about 1 per cent more manganese than the average plain carbon steel, is rapidly entering general service. To what extent this type may be

used is not yet completely known. The higher-alloy steels, represented by the 3200, 3300, and 3400 series, are more expensive but are sometimes required to obtain physical properties beyond the capacity of the lower-alloy steels. The 3300 series finds its most important service in carburized armor plate.

In average service, the type of steel that will give the physical properties desired at the lowest cost should be employed, with the exceptions already noted. Reaching for comparatively slight improvement is rarely worthwhile. Alloy steels have their fields of service, but the value of the less costly plain carbon steel should not be overlooked, for the physical properties obtainable are satisfactory for a wide range of service. Because of this and because of the usually lower cost, carbon steels are more extensively used than alloy steels. On the other hand, alloy steels are generally made with more care, and some alloying elements are cleansing agents that improve condition. Well-made carbon steel, however, within its range of properties, will meet most requirements.

Physical Properties and "Strength."—Materials in service are required to stand up against various kinds of stress both static and dynamic, and the "strength" of a material may be defined as ability to resist applied stress. Unfortunately, there is no standard test for resistance to dynamic stress that is comparable to the tensile test for accuracy and that can be so widely applied. But the tensile properties will usually indicate, although not always, resistance to dynamic stress by the ductility in relation to the tensile strength. Tensile strength is sometimes confused with strength in the general sense—ability to resist any and all stresses—an error that is sometimes made by experienced engineers as well as by laymen. Specifications have been written for steel of high-tensile strength to resist shock and rapid alternating stresses, but such steel may be weak in its resistance to these dynamic stresses because of low ductility. High tensile strength means low ductility approaching brittleness. Such misunderstanding was largely due to the introduction of alloy steels with the properties of high tensile strength and fair ductility, steels that have physical properties beyond the capacity of plain carbon steel. For example, compare the physical properties in Table I. The tensile properties of hardened carbon tool steel are indicated by *A*. The tensile strength is high, but the ductility is low. Steel in this

condition is brittle and will break easily under shock. A hardened alloy steel of much greater strength and ductility is represented in *B*. Such steel is apparently tougher, but the properties do not necessarily prove good resistance to shock and other dynamic stresses. The specification of such properties for the steering knuckle of an automobile, *to take full advantage of the physical properties of the material*, resulted in failure because steel in this condition is too hard to resist the stresses that such a part must bear. For this purpose, the properties represented by *C* would be more desirable, although a somewhat higher tensile strength might sometimes be preferred. High tensile strength is undesirable for resistance to dynamic stresses but finds a field for service in resistance to torsion, compression, and tension uncombined with other stresses and in resistance to rubbing or abrasion.

The Test of Service.—Tensile properties are easily determined and are directly connected with properties determined by torsional or compressive tests. They therefore serve as a standard by which condition can be described and resistance to stress measured. The information given by the tensile properties can be supplemented by information obtained by dynamic tests, but such tests can do no more than approximate the stresses of service. Static tests are more representative, but all laboratory tests are necessarily confined to one type of stress and usually under one set of conditions. Stresses in service, on the other hand, may be complex and may act under widely varying conditions. Laboratory tests may show that a material is in perfect condition and that the physical properties are satisfactory, but nevertheless failure in service may occur because of unknown stresses, unforeseen or accidental. The laboratory cannot duplicate all the conditions of service, and information gained by laboratory test must be supplemented by information gained by the results of trial in service.

Designing to Prevent Failure in Service.—Failure in service is sometimes due to poor condition but is much more commonly due to overstress, for which ignorance, accident, or faulty design may be responsible and mechanical rather than metallurgical conditions. The cause of such failures is often obscure, and the steel or the treatment suspected—wrongly but following natural logic. The type of steel, the treatment, the physical properties, one or all may be changed, perhaps, several times

but without success. The design may then be changed and failure ceases. Change in design may, for some other reason, accompany a change in steel and prevent further failures, but credit will usually be given to the steel.

Because mechanical sources of trouble are often hard to detect, the microscope has been extensively employed in seeking out flaws in steel that might be responsible for failures. Flaws exist and are not so hard to detect, but the microscope sometimes brings out defects almost as obscure as a source of trouble as some mechanical conditions. Frequently, the report will be that "microscopical examination reveals no defects in the material" but goes no farther. Less emphasis is now laid upon minor flaws in steel that are almost always present, but more is laid upon mechanical conditions as a cause of failure. Change in design is the only remedy for faulty mechanical conditions, not change in the type of steel, in the physical properties, or in the treatment. Such conditions are responsible for trouble in hardening tools as well as in structural service, and because they are not always recognized as responsible, the metallurgist or steel treater is frequently called upon to seek out and remove the cause of failure, material and treatment being a convenient alibi. Steel treating, therefore, requires some knowledge of the general principals of designing for service. The effect of stresses will, therefore, be discussed briefly, and common sources of failure illustrated by practical examples many of which will be taken from the automotive field, a great laboratory for the test of service.

The Factor of Safety.—In designing for service, the elastic limit in tension is the conventional starting point in determining the strength of a steel part. From his own experience or from the experience of others the designer knows the combination of elastic limit and ductility required for the particular purpose and selects accordingly from the range between the maximum elastic limit with minimum ductility and the minimum elastic limit with maximum ductility. From the elastic limit selected the size required to carry the load is calculated. Experience shows that greater strength than that calculated is necessary to provide for unknown or combined stresses, if failure is to be avoided. The ratio of the actual strength required to that calculated as necessary is known as the "factor of safety," sometimes called the "factor of ignorance." The allowance

made will depend upon the service required and, also, upon the hardness (tensile strength) and ductility of the material. For stresses that are almost purely tensile, torsional, or compressive, the factor of safety will be much lower than if such stresses are combined with dynamic stresses, and the ductility required will also be less. Live loads require greater ductility than dead loads.

Physical Properties *versus* Size in the Factor of Safety.—When carbon steels were the only type available, the factor of safety was obtained by increasing the size of section and standards were established. The introduction of alloy steels reversed the process somewhat because of the great increase in tensile strength that became possible and without a corresponding loss in ductility. By the use of alloy steels, sizes could be reduced, at least for tensile, torsional, or compressive stresses not combined with other stresses. Designers went as far as they could in raising the elastic limit only to find that ductility was still a necessary factor. Steel of high-tensile strength—hard steel—does not follow the rules laid down for more ductile steel, and to this alloy steels are no exception. In bending, for example, a very hard steel will break under a far smaller load than will a more ductile steel. In straightening, the pressure must be increased as the elastic limit is raised; but near the maximum, breakage will suddenly occur under a reduced load. For illustration, presume that a pressure of 60,000 lb. is required to straighten a bar of moderate hardness, *C* in Table I, for example. If the hardness is greatly increased, breakage may occur under a load as low as 25,000 to 30,000 lb. For resistance to dynamic stress, particularly shock, high-tensile strength is to be avoided. For purely static stresses, increase in the elastic limit by using alloy steel, can replace increase in size sometimes entirely, but sometimes only in part. For dynamic stresses, an increase in the elastic limit can replace size in the factor of safety to a much lesser extent.

Resisting Shock.—Ability to resist shock depends, to some extent, upon the way in which it is applied, whether in combination with compressive stress, as upon the face of a hammer or stamp, or in combination with bending, applied at the free end of an arm. But toughness is essential for resistance to shock, meaning an elastic limit high enough to resist the stress but not so high that too little ductility remains with brittleness as a result. A hammer is never made of the hardest steel. Steel

must also be tough to resist bending under shock. The factor of safety for resistance to shock is, therefore, usually gained by increase in size.

Alternating Stress.—Alternating stress far below the elastic limit is often responsible for failure and is one of the bugbears of designers who place too much dependence upon physical properties, particularly if such stress is also combined with shock. Various laboratory tests have been devised for determining and measuring the effect of alternating stress. One measures the effect of alternating stress with a bar of standard length and diameter held at one end in a rotating device. Weights are hung upon the end, and alternating stress produced by rotating the bar.

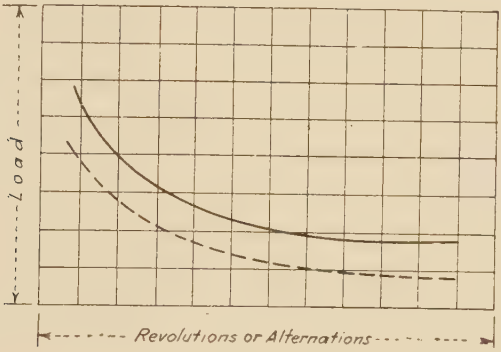


FIG. 13.—Typical alternating stress curves.

The results of testing under increasing loads are shown in the upper curve of Fig. 13. As with most stresses, the margin between eventual failure and indefinite life is small, a point of importance. Slight increase in the load applied in service is sometimes responsible for failure because the endurance limit has been passed. Resistance to alternating strength seems to be in proportion to the tensile strength. The limit of resistance to alternating stress, the *fatigue limit*, is considered to be about 50 per cent of the tensile strength, although some results place it at 40 per cent. Some authorities consider alternating-stress tests as simply other methods for determining tensile strength. Increase in the tensile strength, however, aids in resistance to alternating stress and bending, provided that there is sufficient toughness to resist shock. Too much dependence must not be placed on tensile strength in resisting combined stresses part of which are

dynamic. A slight increase in size is often a better method of obtaining a factor of safety than a great increase in tensile strength. The two methods are often combined.

The Nick Effect.—The lower curve of Fig. 13 illustrates the weakening effect of a nick upon resistance to alternating stress. This test was made with a notched bar of the same length of the bar with which the upper curve was obtained and of the same diameter at the bottom of the notch. A nick also lowers the transverse strength. The effect of a nick or a sharp internal corner or of a sharp external corner has long been known and applied in breaking sticks of wood or bars of steel, but is not always so clearly recognized in design, although there has been much improvement in recent years. Even comparatively small scratches and tool marks, changes in the size of section, and minor surface imperfections may cause breakage. Automobile owners are generally familiar with breakage due to the nick effect, common in threaded rods.

Typical Failures Due to Nick Effect.—The factor of safety is so reduced by a nick that resistance to stress may be close to the

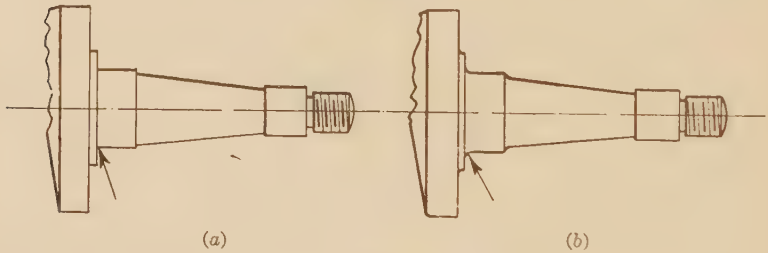


Fig. 14.

low limit and any slight increase in stress may, therefore, suddenly cause failure of parts that have previously given good service. Breakage of rear-axle shafts through tool marks began when the weight of a heavy car was increased by only 150 lb. Changes in construction that seem minor are often followed by a series of failures due to alternating stress combined with the nick effect for which the factor of safety cannot be determined with any accuracy. Comparatively slight increase in the weight of a motor car or truck is often responsible for fracture in the threads of struts and brake rods. Sharp corners in keyways, square bolt holes, and other parts where two surfaces meet at

an angle can do much damage. Sharp external corners are almost as dangerous as sharp internal corners.

Figure 14 (*a*) illustrates an early design for the arm of a motor-car steering knuckle; (*b*) the modern type with ample fillet The first failed frequently, the second fails rarely. This arm must resist heavy shock and alternating bending stress the intensity of which cannot be predicted. Ample size provides the necessary factor of safety, and a large fillet in the corner removes the nick effect. Figure 15 A illustrates a method of fitting shafts that was common in "buggy days" and was carried over into early motor-car practice, a method now obsolete. Failure at the squared end was due more to the sharp corners at which the stress was concentrated then to the reduced size. A change

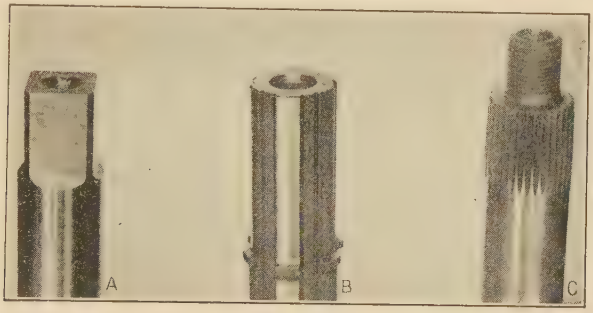


FIG. 15.

to the type of fit shown in Fig. 15 C stopped breakage. Before this change different types of steel were tried and elastic limits were varied from 90,000 to 200,000 lb. per square inch, but without success. Figure 15 B illustrates a conventional spline now generally preferred for fitting.

The Nick Effect in Tool Hardening.—In tool hardening, poor design is probably responsible for more trouble than poor steel or poor treatment. The sharp external corner is often a source of trouble because the stresses set up by hardening find here a weak place, and hardening stresses are usually the greatest at sharp corners. Hardening stresses, like other stresses, find release through nicks, sharp corners, and surface imperfections. Numbers stamped on a tool with steel stencil are occasionally responsible for breakage. Sharp corners may be required because of the nature of a tool, but designers sometimes permit holes near the edge or may introduce sharp corners where fillets should be added.

Sometimes, the fillet is in the blueprint but not in the piece. Responsibility for breakage, however, is usually passed on under the term "hardening cracks."

Elasticity and Alternating Stress.—The elasticity of steel may introduce alternating stress when use is made of this property, as in springs, and, also, when elasticity is unsought, exemplified by the whip of a long rotating shaft. The modulus of elasticity is practically the same for all steels—all deform to the same extent under the same load below the elastic limit, regardless of physical properties. Elastic deformation (change of shape under loads below the elastic limit) depends upon the unit stress and can, therefore, be reduced by increasing the area. This is easily demonstrated with two bars of the same length, 2 to 3 ft. long, one ½ in. in diameter, the other, 1 in. Clamp one end of each bar in a vise and press lightly on the free end with the hand. The smaller bar will spring easily, but the other will not move noticeably without greater pressure. The same results will be obtained regardless of the hardness of the bars. Elasticity is controlled by size.

The elasticity of a spring depends upon its dimensions, not upon the physical properties of the steel from which it is made, presuming that these properties do not indicate poor condition. Springs are usually heat treated for rather high elastic limits so that the stresses of service will not cause permanent deformation. Springs are naturally subjected to alternating stress and, therefore, sometimes fail because of the nick effect. The physical properties of carbon spring steels are satisfactory for average duty, but alloy steels are sometimes preferred if a high elastic limit is desired, and some types seem to give better service than others, although the line is hard to draw.

Rigidity.—Rigidity, resistance to elastic deformation, likewise depends upon size rather than upon physical properties. Many attempts that have been made since the introduction of alloy steels to substitute higher elastic limits for size have failed because of the whip that resulted. Quite a number of propeller shafts pounded through the floors of experimental motor cars when the size of the shaft was reduced. The principal structural parts of motor vehicles—the frame, the front axle, the rear-axle housing, the crankshaft, and other parts—must be rigid and are, therefore, large enough to permit using steel of comparatively low tensile strength. The frame, for example, is usually

of 1020 or 1025 steel, which can be easily pressed. Greater tensile strength, on the other hand, will be required for front axles and crankshafts. The axle must not bend permanently under unexpected impact, if some object is struck, as sometimes happens. The crankshaft requires some hardness on pins and bearings to reduce wear and to take care of the torsional stress. High elastic limits may be required for heavy duty, as in aircraft engines. Crankshaft failure due to whip, sometimes combined with the nick effect, has been common. A very slight increase in size, or ample fillets, usually stops the trouble. Attempts to meet the problem by increasing the tensile strength have not been so successful. Failure in machine tools, if only in accuracy, are frequently due to lack of rigidity, particularly in arbors. Rigidity is an important item in design and often accounts for the success of one machine in contrast to the failure of another, particularly if the first uses steel of comparatively low tensile strength and the second, steel of comparatively high tensile strength.

Torsional Strength in Service.—Steels of high tensile strength find their greatest field of service in resistance to torsion or compression uncombined with other stresses but more in compression than in torsion. The minimum size of a shaft may be fixed by the necessity of avoiding whip, because the connection with other working parts so requires, or for other reasons, and thus any marked increase in the elastic limit of the steel used may become unnecessary. Heat-treated shafts usually require straightening, an operation that becomes increasingly difficult as the elastic limit is raised even if heating is resorted to. Substituting a high elastic limit for size is not always advantageous, because the torsional strength of a shaft varies in proportion to the cube of the diameter, and a comparatively small increase in the diameter, therefore, provides a marked increase in strength.

Compressive Strength in Service.—Compressive strength has no such limitations. Ball and roller bearings, gears, stamps, dies have heavy duty to perform, duty that would be impossible if not prohibitive if steels of high tensile strength were not available. For resistance to high compression, maximum hardness is obtained with high-carbon steel, for example, 1095 for average duty and 51100 or 61100, chromium steels, for particularly heavy duty. Carburized steel is employed for moderate pressure if ductility, a function of the core, is also desirable.

For compression under impact, as in stamps, requiring both hardness and ductility, high alloy steels are used—for example, the 12 per cent manganese steel. All are heat treated for a maximum or nearly maximum hardness, the high-carbon steels for a scleroscope hardness 90 to 100. For moderately high compression requiring also some ductility, medium carbon steels are used—for example, 2350, 3350, 3450, 5150, 6150, primarily gear steels. For such service, these steels are heat treated for a scleroscope hardness of approximately 70.

Resistance to Compression and Abrasion.—The sliding or rolling of one surface over another under pressure causes wear or abrasion, and for resistance to abrasion the surfaces are hardened. Compression and abrasion are commonly associated as in examples given in the preceding paragraph concerning gears, ball, and roller bearings. Resistance to abrasion, like resistance to compression, depends upon high tensile strength but requires comparatively low ductility. Resistance to abrasion is proportional to the hardness of the surface, neglecting the factor of lubrication, and inversely proportionate to the pressure. Increasing the surface hardness may prevent abrasion, provided that unit pressures are not too high. Hardness, however, is limited, and maximum hardness does not mean perfect resistance to abrasion under any load. If unit pressures are too high, increasing the hardness of the surface is one remedy for pitting provided that the maximum hardness obtainable has not been reached. Otherwise, an increase in the area of contact is the only remedy. The load, of course, can be reduced.

Inspection for Service.—Mechanical conditions that so often cause failure in service cannot always be foreseen or detected by laboratory or experimental tests. Experimental models may give satisfactory results, and yet failure in actual service will occur because of different conditions. For example, forgings made by hand for the experimental model may prove satisfactory, but forgings struck in the die fail in actual service because of some seemingly small difference in size or shape. Gears that stand every test for quality fail in service because of misalignment sometimes due to lack of rigidity in the construction of the machine as well as to poor assembly. Gears are designed for contact on the pitch line but fail when contact is too far above or below or, in bevel gears, when contact is mostly at the heel or toe. An internal-combustion engine may run successfully on the test

stand, but in service one part or another sometimes fails because of some increase in stress not foreseen. These, and a host of other mechanical conditions, are sources of failure, a fact not always recognized because of the convenient alibi of "defective material."

A knowledge of the results of service is as necessary as a knowledge of the physical properties and condition of the material employed. Laboratory tests for physical properties and condition are important in determining the suitability of a material for service and the reason for failures in service but should be supplemented by inspection of parts that have worn out or that have failed in service to determine the effect of mechanical conditions. Unless laboratory tests definitely show failure to be due to defective material or to variation from specifications, faulty mechanical conditions should be suspected as the cause of failure. Direct evidence of mechanical faults is sometimes hard to find, and indirect evidence should, therefore, be sought. The remedy for such failures is sometimes a change in the physical properties of the steel, but more often a change in construction or in the size of section is necessary, as already described.

The strongest indirect evidence of overstress due to faulty mechanical conditions is continued failure at or near the same point. This and other indirect evidence may prove the existence of the nick effect even if direct evidence of a nick is destroyed by fracture. Failure at sharp corners at or depressions is direct and positive evidence of the nick effect. Pitting under abrasion and compression is direct evidence of too heavy unit pressure. Failure due to alternating stress is almost always indicated by the appearance of the surface of the fracture, which will be smooth because of abrasion, except in the area at which final fracture occurs. A crystalline center surrounded by a smooth surface is typical of "fatigue" fractures. These are some of the indications of failure due to overstress for which faulty mechanical condition is often responsible, a more common cause of failure than defective material, and which therefore must be taken into account in inspection for service.

CHAPTER IV

QUENCHING AND THE SOLUTION STRUCTURES

Quenching Once a Mysterious Process.—Quenching is one of the most important operations in steel treating because results so frequently depend upon the rate of cooling. The more spectacular heating operation has been given greater general attention, but the smiths of long ago knew that success more often depended upon the method of quenching. In popular literature the forge has received frequent mention and has been highly favored in poetry and romance, but few if any references to the quenching bath will be found. There was little to picture and no substance for romance. In more technical literature, lack of reference may be due to the secrecy that so often shrouded quenching mediums and methods. Much of this secrecy was due to the mysterious results obtained by quenching, results often widely different even with the same steel and same heating and same medium but differing more frequently with different mediums. Such variations led to much experimentation and to many different quenching mediums that were usually kept profoundly secret. Many of those that were not kept secret are decidedly wierd. Water in which grass, roots, and other vegetable matter was steeped is a milder quenching medium than "the blood of a Nubian slave." Condemned criminals and slaves, alive or dead, were favored "solid quenching mediums."

Quenching was considered a mysterious process because there was no way of determining the exact results obtained. That the steel took "something" from the bath and that this "something" differed with different quenching mediums was a plausible argument in an age less inclined toward research. The hardener, knowing that the results varied, experimented. If he happened to stumble upon a composition that seemed to meet his requirements, another secret formula was born. Of such formulas, a few had some reason for existance, others show the power of the imagination and may be classed with the

left hind foot of the graveyard rabbit. Secret quenching mediums have almost entirely disappeared, but some may still exist. Secret formulas are scarce because quenching is no longer a secret process. Any mystery that remains usually takes the form of a high-priced medium presumed, because of the price, to have exceptional power.

Quenching Structures.—The microscope, a very helpful tool, has cleared up much of the mystery surrounding the results of quenching by making it possible to see the structures produced. As revealed by the microscope, such structures, of which a series exists, are homogeneous in contrast to the mechanical mixture pearlite and are solid solutions fixed by rapid cooling from above the critical range. The separation of ferrite and cementite on cooling from above the critical range requires time and will be suppressed by more rapid cooling, thus fixing the solid solution that exists normally above the Ac_3 point. This simple explanation, however, does not tell the whole story, because several structures can be produced that have different physical properties, almost like different metals. Their production in steel treating, moreover, depends upon many variable conditions. Not all steels are quenched to obtain solution structures. Some are normally solid solutions because their critical temperatures are below ordinary atmospheric temperatures. The majority of commercial steels, however, have critical temperatures so high that relatively rapid cooling is required to fix the structure. They are called "pearlitic" steels because proper cooling from above the critical range will result in a pearlitic structure. To such steels discussion will be confined except for occasional reference.

Quenching has been described as relatively rapid cooling from temperatures above or within the critical temperature range by the use of mediums more drastic in effect than still air, of which water, oil, molten lead and salts, and an air blast are examples.

In this sense, the term applies to the rapid cooling of steels that are already in solid solution as well as to pearlitic steels. The former, however, are quenched to retain a particular structure or for other reasons. The latter are quenched to fix solution structures.

The results of quenching vary because different structures having different properties are produced. Of these four have been recognized and named austenite, martensite, troostite,

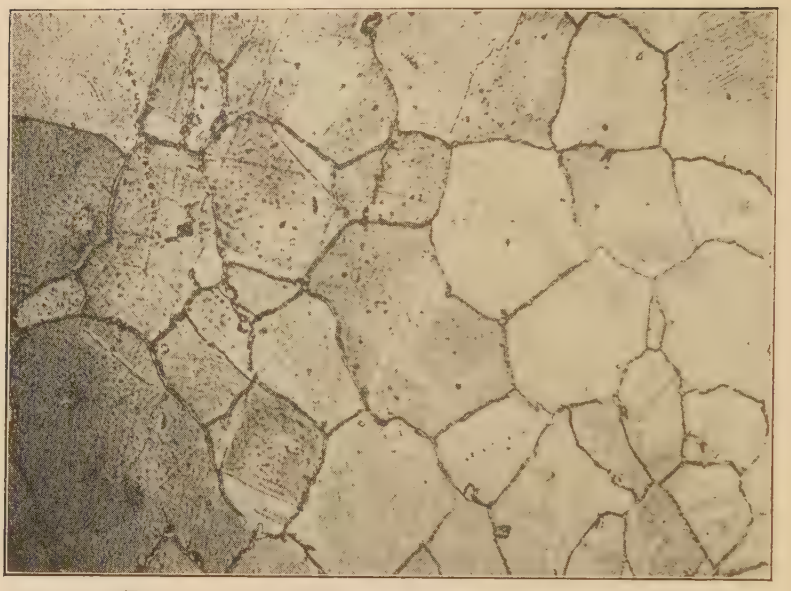


FIG. 16.—Austenite, high-speed steel. 150 diameters.

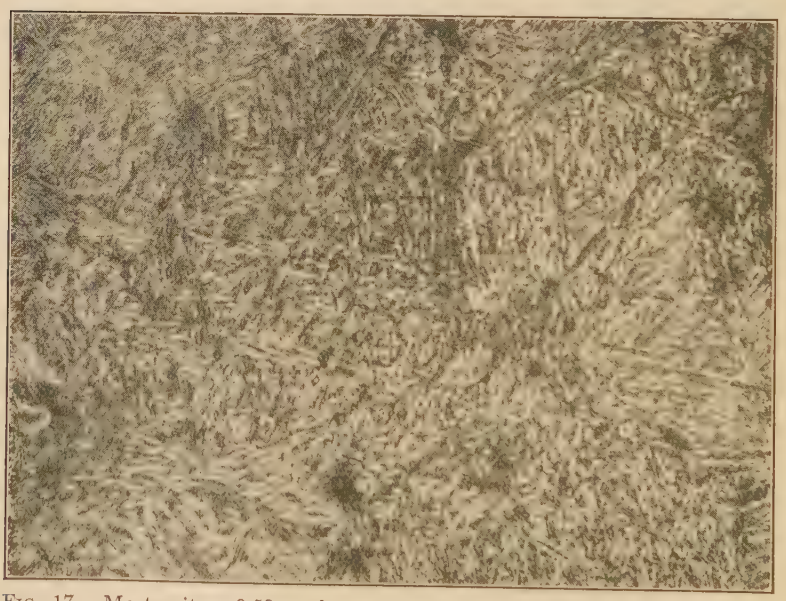


FIG. 17.—Martensite. 0.50 carbon steel, water quenched. 500 diameters.

and sorbite, in honor of metallurgists who were pioneers in the scientific investigation of the structures of steel. Austenite, shown in Fig. 16, a photomicrograph of high-speed steel, is most

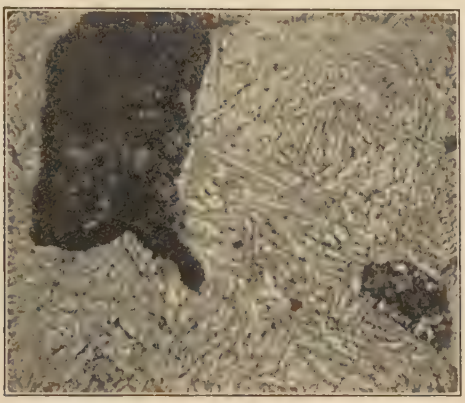


FIG. 18.—Martensite with troostite 1.10 per cent carbon. 500 diameters.

representative of a solid-solution structure. Martensite, the constituent of hard steel, is shown in Fig 17. The characteristic needles and plates can be seen in this photograph and, also,

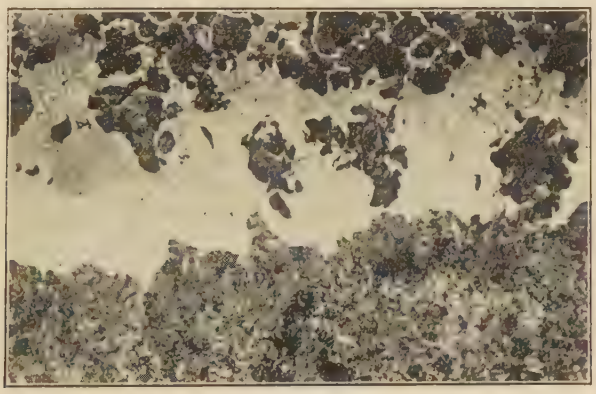
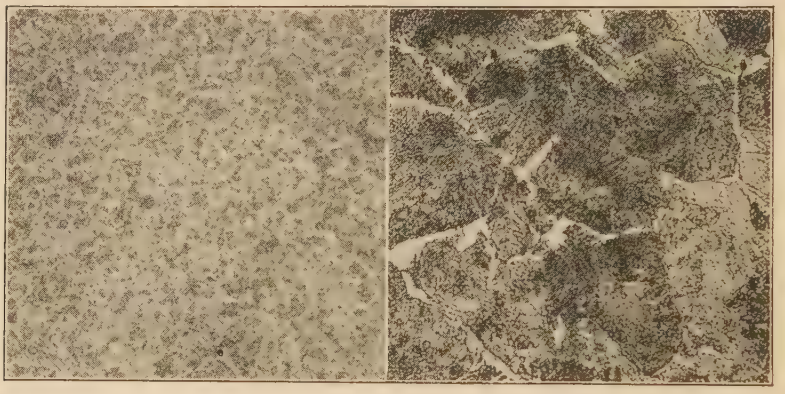


FIG. 19.—Case-hardened 1015 steel troostite in martensite; troostite grading into sorbite. 100 diameters.

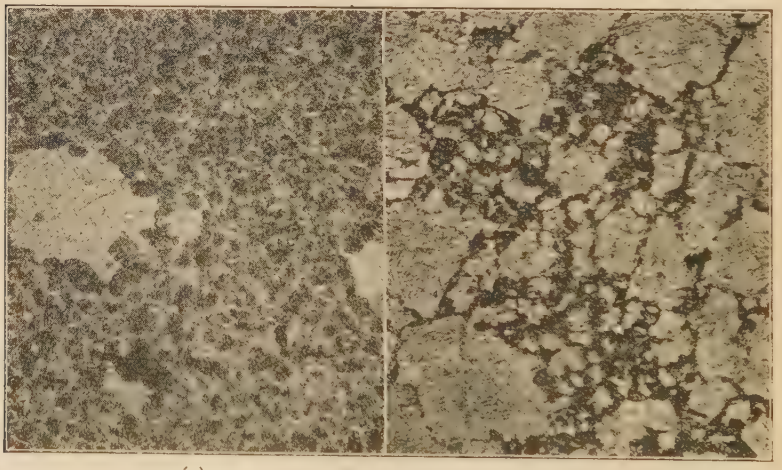
in Figs. 18 and 21. Troostite, shown for contrast with martensite, appears in Figs. 18 and 19 as a black mass in contrast to the lighter-colored martensite. The color of martensite varies, after etching, from white to light yellow. Sorbite, shown in

Figs. 20 (*a*) and 20 (*b*), resembles pearlite under low magnification but is homogeneous and cannot be resolved into different constituents even under the highest possible magnification.



(*a*) (*b*)

Fig. 20.—(*a*) 1035 steel quenched water 1550° F. Drawn 1100° F. (595° C.). 100 diameters. (*b*) 1055 steel quenched water 1450° F. Drawn 1200° F. (650° C.). 500 diameters.



(*a*) (*b*)

Fig. 21.—3140 steel, oil quenched. 100 diameters. (*a*) Soft spot; troostite and martensite. (*b*) Normally hard; martensite and troostite.

Factors Governing Structure Produced by Quenching.—The existence of so many "solution structures" will be better understood if austenite is considered as the true solid solution,

and the others, martensite, troostite, and sorbite, in the order named, as stages of transition between austenite and pearlite. The particular structure obtained by quenching depends upon three factors, namely, the rate of cooling, the content of carbon, and the content of alloying elements. All work in the same direction. For example, a plain carbon steel will be pearlitic if cooled in still air, but a steel containing alloying elements will be sorbitic or may even be martensitic, this depending upon the amount of such elements that is present. Again, martensite may be produced by quenching a piece of 0.90 carbon steel in water, but a similar piece containing only 0.40 carbon will probably be troostitic if so quenched or contain both troostite and martensite. Sorbite will result if the carbon is still lower. But if an alloying element is added without changing the amount of carbon or the conditions of quenching, the result will be higher in the series than with a plain carbon steel. Quenching that produces troostite in a 0.40 carbon steel will produce martensite in an average 0.40 alloy steel. A higher or lower structure in the series will result if the rate of cooling is increased or decreased. For example, a piece of 0.90 carbon steel may be martensitic if quenched in water or troostitic if quenched in oil.

Abnormal Steel.—The effect of the rate of cooling is marked if steel is in a condition that has been termed "abnormal." This condition occurs usually in case-hardening steel but sometimes in tool steel. Microscopical examination shows a peculiar arrangement of the cementite, particularly in hypereutectoid steel (steel containing more carbon than pearlite). In Fig. 22 (*a*) is shown a normal carburized steel. The cementite is continuous around the grains. In Figs. 22 (*c*) and (*d*) the cementite is not completely continuous, and these samples are slightly abnormal. Sample (*e*) is exceptionally abnormal, the cementite being badly broken up. This sample will harden with difficulty, requiring very rapid cooling. Its behavior is much like that of a steel far lower in carbon.

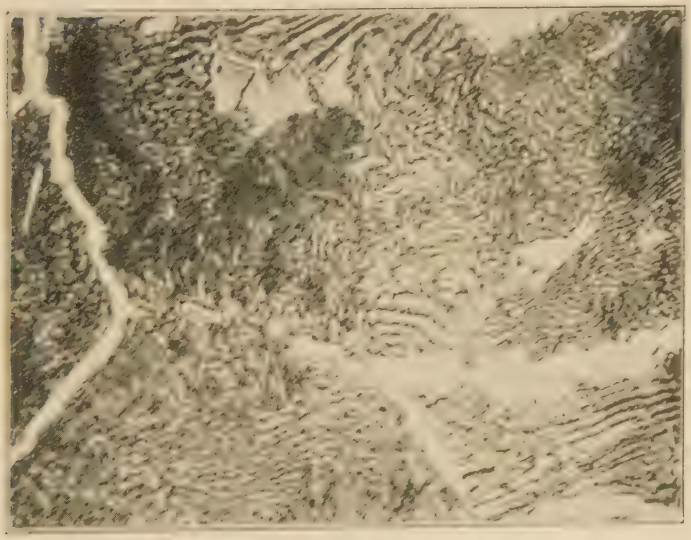
The cause of abnormal steel is still a matter of opinion. Dissolved oxides have been held responsible and, also, *overkilling*, *i.e.*, holding molten steel in the furnace a long time to remove gases, a belief backed by some evidence. Trouble due to abnormal steel is unknown in many plants, but in others, this condition has been responsible for failures in hardening. Abnormal steel requires more rapid cooling than normal steel to avoid the for-

(*a*)

(*b*)

FIG. 22. – Illustrating normal and abnormal carburized steel. 500 diameters. (*a*) Normal, (*b*) normal, showing varying grain size.

(c)

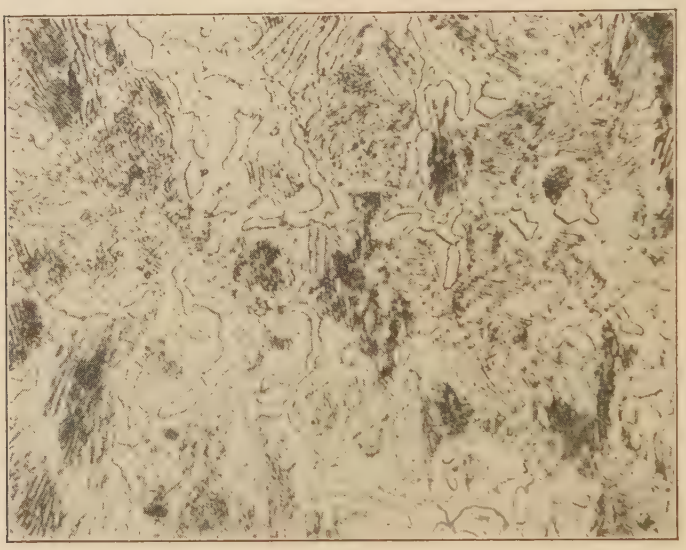


(d)

FIG. 22 (Continued).—Illustrating normal and abnormal carburized steel. 500 diameters. (c) Slightly abnormal, (d) slightly abnormal.

mation of troostite, and it is possible that much of the trouble in hardening has been due to improper quenching, a point that will be discussed later. Plants equipped with proper quenching apparatus seem to have little difficulty in hardening.

Variation in grain size is common in carburized steel, as illustrated in Fig. 22 *B*. Grain size has been stated to indicate normality or abnormality, but upon this point there has been considerable argument. From the best evidence, grain size



(*c*)

FIG. 22 (*Continued*).—(*c*) Illustrating very abnormal carburized steel. 500 diameters.

has little effect. Some operators, however, follow grain size even though the results of hardening are good. The normality or abnormality of carburizing steel is determined by carburizing and later examining the unhardened sample under the microscope.

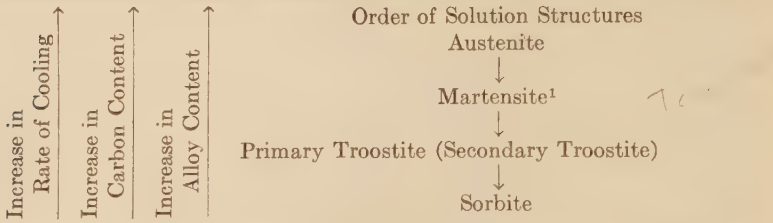
Unfortunately, abnormal steel offers a convenient alibi for steel that has not been properly hardened and may be an excuse for poor quenching practice. Some shapes of steel are naturally difficult to harden. Camshafts are particularly notorious for soft spots. If only one or two such parts give trouble in hardening, the difficulty probably lies in the method of quenching and not in the steel. Abnormal steel can cause trouble, but this

fact is a strong argument for proper facilities in quenching, to which attention will be given. For the condition the steel maker is evidently responsible, and if his practice is correct, the steel made will not be abnormal.

Retaining Quenching Structures.—At ordinary atmospheric temperatures, pearlite is the natural stage of equilibrium, and austenite fixed by quenching is farthest from that stage and, therefore, the most difficult to obtain or rather, to retain. A 0.90 carbon steel will generally be martensitic after very rapid cooling, although, as later evidence will indicate, austenite is probably fixed in the first stage of quenching and is later transformed into martensite. Austenite can, by very rapid cooling, as in iced brine, be fixed in carbon steel containing 1.50 per cent of carbon. By introducing the third factor, alloying elements, austenite is more easily retained. To retain the other structures, martensite, troostite, and sorbite, and in that order, less is required of the three factors.

Effect of Tempering upon Quenching Structure.—Transition from one structure to the next below results from reheating after hardening and continues through the series as the temperature is raised. Austenite passes into martensite, martensite into another stage at a higher temperature, and troostite into sorbite. Martensite is not converted into troostite by tempering, at least not into troostite in the form illustrated—a point of importance in hardening. To keep the order established, the structure resulting from reheating martensite is called "secondary troostite," the form obtained by quenching being known as "primary troostite." Further mention of troostite will refer to the primary form only. If the temperature of drawing rises above the critical range, slow cooling will result in pearlite. The drawing operation is limited, however, by the lower end of the critical range. The quenching structures obtained by drawing depend upon the temperature employed, not upon the subsequent rate of cooling. The interrelationship of the structures and the effect of the three factors that control them in quenching can be shown in a diagram.

Effect of the Three Factors on Structure Produced by Quenching



Comparative Rates of Cooling a 1.0 Per Cent Carbon Steel in Effect upon Structure Produced by Quenching

Austenite	Very rapid cooling will produce but not retain completely. Increase in carbon required.
Martensite	Rapid cooling as in water.
Troostite	Slower cooling as in oil.
Sorbite	Still slower cooling as in molten lead.

Combination of two adjacent structures may also result.

[1] Arrows indicate transition on tempering.

Physical Properties and Structure.—The solution structures have markedly different physical properties. No one degree of hardness can be assigned to any one structure because of the different conditions under which they can be produced. For illustration, however, a range of hardness will indicate the differences qualitatively. In scleroscope-hardness numbers, martensite may be considered as having a hardness of 90 to100; austenite, 60 to 70; troostite, 40 to 50; sorbite, 30 to 40 in comparison with 20 to 30 for pearlite. These figures are not accurate for all conditions but are fairly representative. In actual testing with different kinds of steel, hardness will vary considerably. A more accurate comparison can be made by means of the physical-property charts and tables in Chap. III, although these do not include purely martensitic or troostitic (primary) structures. The figures, however, illustrated the change of physical properties with change of structure as the drawing temperature rises. Structures obtained by such treatment are illustrated in Fig. 43. With carbon or the lower-alloy steels the structure after quenching is martensitic, or both martensite and troostite may be present, as in Fig. 21, this depending upon the rate of cooling and carbon and alloy content. The difference in the physical properties resulting from different rates of cooling is illustrated in the charts and tables by a comparison between the results of quenching the same steel in oil and in

water. The properties of austenite are, perhaps, best illustrated by manganese steel (12 per cent) with a tensile strength of about 150,000 lb. per square inch and a reduction of area approximately 50 per cent obtained by water quenching.

Applying Structure to Service.—Of these structures martensite is the structure at which steel treating usually aims, because it is the hardest, not only when this quality is desired for service but also because it is the best starting point for tempering. Sometimes, however, a mixture of martensite with the softer troostite is desired because of a combination of hardness and toughness that results, for example, in oil-quenched springs of carbon steel. For ductility, sorbite may be desired. On the other hand, austenite has certain properties that have been described by the term "tough hardness," illustrated by manganese steel. The steel treater or user of steel can obtain a wide range of physical properties by varying the structure or can often obtain a particular result in a number of different ways. For example, he may be able to obtain similar physical properties by quenching in water and tempering or by quenching in some other medium that will cool at a lower rate without subsequently tempering. Or he can change the composition of the steel employed, thus introducing the other factors.

Effect of Carbon and Alloying Elements.—The rate of cooling is, perhaps, the most important factor in steel treating, but its range is limited. Even with the fastest possible rate of cooling, a desired result may be difficult to obtain if not impossible. Under such a condition, the carbon content can be increased or alloying elements added or increased if already present. If, for example, a 0.40 carbon steel cannot be made so hard as desired by any method of cooling, perhaps this result can be obtained by increasing the carbon to 0.90 per cent. Or if the hardness obtained with 0.90 carbon steel is too great, a 0.40 carbon steel may give the condition desired. The range of carbon steel is limited, however, and if too limited, alloying elements can be introduced to increase the hardness or to increase the tensile strength. Alloying elements also permit reducing the rate of cooling below that required for carbon steels, an effect that is cumulative as the amount of such elements increases. For example, the addition of manganese to tool steel permits hardening in oil instead of water, which is usually required for plain carbon steel. The other alloying elements have the same effect, as illustrated in the charts and tables of physical properties.

Effect of Rate of Cooling.—When the desired composition has been determined and is fixed, the rate of cooling becomes the important factor. It is particularly important if the choice of steels has been limited and results left more to this factor, as is usual in practice. When the alloying elements are present in large amount, the rate of cooling is of less importance. The desired result may be obtained by a relatively slow rate of cooling—by an air-blast, for example and more care required to avoid too rapid rather than too slow cooling. With the more commonly used commercial steels, however, from carbon steel to the average chromium and chromium nickel steels, the close or reasonably close control of the rate of cooling in quenching is necessary, and to such steels further discussion will apply. The rate of cooling is governed by a number of conditions that will be considered—for example, the nature of the quenching medium, its temperature, the dimensions or mass of the piece quenched and its quenching temperature.

Industrial Quenching Mediums.—In industral practice, the rate of cooling is controlled by the use of different quenching mediums that absorb heat at different rates. In ideal practice, the rate of cooling would be regulated by selecting from a series of quenching mediums one that would give the exact result required. But, unfortunately, in industrial practice there is no series in which each medium varies but little in cooling power from the one adjacent. The quenching mediums available cover a wide range, but between the different types there are gaps that are hard or impossible to fill, for example, between oil and water, the quenching medium most commonly used. The common quenching mediums can be listed in approximate order of cooling power as follows:

Water and water solutions	Iced brine.
	Cold running water; brine and caustic-soda solutions.
	Still water.
	Warm water; boiling water and hot solutions.
Oil	Light: kerosene, paraffin oil, crude mineral oil.
	Medium: lard oil, fish oil, cottonseed oil, mineral oil and mixtures; heavy mineral oil.
Semisolids	Mineral grease, tallow, soap.
Molten baths	Lead, salts, cyanide and cyanide mixtures.

Water and Water Solutions.—The exact position of some of the quenching mediums in such a table is in doubt. For example, opinions regarding the relative effects of water and brine have received much discussion. Experimental results are often misleading because of the variation in conditions. The general opinion, expressed by several authorities, is that brine is more drastic than still water but that cold running water is more drastic than brine. Brine and soda solutions, however, seem to remove the scale formed on heating more easily than water does, a possible explanation of the apparently greater cooling power.

Quenching Oils and Greases.—A similar difference of opinion exists regarding the effect of the different oils. Before mineral oils were available, steel-treating practice made use of the animal and vegetable oils that could be obtained, of which fish oil, lard oil, cottonseed oil, and even olive oil are representative. Present-day practive, however, employs the cheaper mineral oils with which a considerable range of cooling power can be obtained. Mixtures of lard oil and mineral oil can be found on the market, perhaps a compromise between the mineral and natural oils, some of which are still employed on a small scale.

Of the light mineral oils typical examples are kerosene, crude oil, paraffin oil. These have no extensive use in steel treating because of the fire hazard. All of them ignite at comparatively low temperatures. These oils, however, help to fill the gap between water and oil but are sometimes almost as drastic as water. They are convenient for thinning heavier oils. Another advantage is their comparatively low cost, but this is sometimes balanced by the care required to avoid fires. A rapid and constant flow is required to avoid overheating, and as little as possible should be left in open tanks near furnaces.

The mineral oils commonly employed have high flash and ignition temperatures and, therefore, present no particular fire hazard. They must be kept cool, however, at least below the flash point to avoid ignition and, also, to control the rate of cooling on quenching. For quenching, these oils are usually held at temperatures between 50 and 120° F. (10 to 50° C.). The cooling power drops off rapidly as the temperature rises above that range. On the other hand, the heavy mineral oils are almost solid at ordinary temperatures and must be heated. These heavy oils find service in the treatment of spring steel when tempering after quenching is to be omitted.

The semisolids—greases, fats, soap, and others of the same nature—find a special but limited field as quenching mediums for very thin sections or for sharp-pointed tools. Gravers are commonly quenched in a cake of soap, a method that gives far better results than a more drastic quench followed by tempering.

Molten baths, like the heavy oils, have a limited field and are used for special purposes, for example, in hardening high-speed steel or in the *patenting* of wire, a process that will be described later. A sorbitic structure is obtained by quenching carbon or low-alloy steel (not too high in carbon) in a molten bath.

Special Quenching Mediums.—Attempts are made to fill the gaps between the commercial quenching mediums by the use of other materials. For example, glycerin and solutions of glycerin in water have been suggested for the gap between water and oil. Glycerin, however, like some other materials that have been proposed, is too expensive for ordinary industrial operations and does not always meet the requirements. The existence of these gaps probably accounts for the use of peculiar quenching mediums in the earlier days of steel treating.

Conditions Governing the Rate of Cooling.—The rate of cooling in a particular quenching medium depends upon the temperature of the medium, the temperature of the piece on quenching, the cleanliness of the surface, the dimensions or *mass* of the piece, and the velocity of flow of the quenching medium. The effect of the temperature of the bath has already been discussed. A change of temperature may alter the rate of cooling. Increase in the quenching temperature also lowers the rate of cooling but ordinarily has little effect upon the structure obtained unless the usual quenching temperatures are considerably exceeded. Higher temperature may sometimes be preferred, however, if austenite rather than martensite is desired, for example. The rate of cooling will be slower if the surface of the piece to be quenched is insulated by scale. But of all the conditions that control the rate of cooling, the dimensions or *mass* of the piece is, perhaps, of the most importance.

Effect of Size of Section, Mass. Depth of Hardening.—The effect of mass has already been discussed in connection with physical properties and illustrated in the charts. Large pieces cool more slowly than small pieces, but this is controlled by the smallest dimension rather than by total weight or total volume. Thin sections require less drastic quenching than thick

sections. For example, a saw blade of 1.0 per cent carbon steel will be martensitic if quenched in oil, but a larger piece of the same steel will be martensitic only if quenched in water. Furthermore, thin pieces of carbon steel may be hardened throughout, but large pieces of the same steel will be hardened (martensitic) near the surface only, and a fracture will have the appearance of case-hardened steel. Below the martensitic layer troostite and sorbite will be found, resulting from the slowing down of the rate of cooling. This is illustrated in Fig. 23. The mar-

FIG. 23.—Case-hardened steel illustrating martensite grading into troostite and sorbite. 100 diameters.

tensitic layer will be hard, but the rest will be soft. The depth of hardening is comparatively small. A thin section can be hardened throughout, but a thicker section will not. Size of section must, therefore, be taken into account.

Effect of the Flow of the Quenching Medium.—The circulation of the quenching medium is necessary to avoid overheating, but the velocity of flow is of more importance in its effect on the rate of cooling. More rapid cooling can be obtained by increasing the velocity of flow, because heat is removed more rapidly. A marked increase in hardness can be obtained by quenching in a rapidly flowing medium even with low-carbon steel. Abnor-

mal steel will harden and soft spots can be avoided if the flow of the quenching medium is rapid. The effect of this more rapid cooling is taken advantage of in hardening, for example in treating bevel gears. The more drastic water quenching that often causes distortion can be replaced by oil quenching if the oil is forced between the teeth under high pressure. Figure 24 shows equipment for this purpose. The surface hardness will not be much less than that obtained by a quench in a tank of water. The effect of a constant change of the quenching medium has long been known and is often demonstrated by the hardener who moves the piece to be quenched to and fro in the bath as rapidly as possible. Not only does he obtain a somewhat greater degree of hardness but he also prevents the formation of vapor pockets through local overheating of the quenching medium.

Vapor Pockets. Local Overheating of Quenching Medium.—Vapor pockets are responsible for irregular hardening and particularly for soft spots. Steam or oil vapor in contact with the surface acts as an insulator and slows down the rate of cooling. As a result, troostite, and occasionally sorbite, is the result rather than the martensite structure generally desired in hardening. The effect of vapor pockets is illustrated in Fig. 21. The two photographs represent closely adjoining surface areas. Vapor pockets are easily formed in recesses and under projections and are not easily avoided in such places unless the flow of the quenching medium is rapid. Oil and water in contact with hot steel quickly vaporizes, and the gas formed is usually hot enough to exert considerable pressure, enough to prevent contact between the quenching medium and the steel. This is easily illustrated by dropping water on red-hot steel. The steam formed has sufficient pressure to prevent contact between the drops of water and the metal.

Local overheating of the quenching medium, without the formation of gas, may have much the same effect as vapor pockets because of the slow rate of heat transfer to a hot quenching medium. Motion in the bath or the transfer of a too small amount of heat may prevent the formation of vapor pockets, but the liquid in contact with the steel may be quite hot, with consequent slowing down in the rate of cooling. The shape of the piece is, again, often responsible for local overheating of the quenching medium. Even with a flow of quenching medium

it is difficult to reach recesses and the interior of hollow cylinders. Again, large sections cool more slowly than small sections and give off more heat. A strong flow may be necessary to avoid local overheating of the quenching medium.

Drastic Quenching. The results obtained by a flowing quenching medium and by increasing the velocity of flow have led to the use of quenching mediums under high pressure, termed "drastic quenching." The tensile strength of low-carbon steel can be greatly increased, far beyond that obtainable by ordinary methods, by drastic quenching. Light oils will give results almost equal to those obtained with water, by applying them under high pressure. By such rapid flow, vapor pockets and local overheating can be prevented. Drastic quenching does not always imply the application of the quenching medium under pressure; the necessary flow may be obtained by motion of the part quenched. For example, large gun barrels (cannon) are often hardened by dropping them vertically into a deep well of water, thus providing flow through the interior of the barrel, where it is most needed. The value of drastic quenching has been recognized for some time, but commercial applications are comparatively recent. Equipment for drastic quenching is now quite common, although there is still room for a more extended use of this method. A greater industrial application of drastic quenching can be expected now that its value is better known.

Time Quenching.— The hardness obtained with any quenching medium may be controlled to some extent by the time during which the steel remains in the quenching bath. If the piece being quenched is removed while hot, the residual heat will draw the steel. This method may be used to avoid a separate drawing operation, but such a process requires some skill. The common term for such treatment is "time quenching," a name derived from the control of results by timing. Time quenching is used quite commonly to save the expense of a separate drawing operation but may also be used when a separate draw is to follow. It is sometimes necessary, particularly with large pieces, to use a drastic quenching medium to obtain sufficient hardness, and as a result breakage may occur if cooling is carried to or nearly to the temperature of the bath. Such breakage can be avoided without much sacrifice of hardness if the steel is removed from the bath while warm, the result

desired being obtained by removing from the quenching bath after a predetermined length of time.

Time quenching, with oil as the quenching medium, is common practice in the treatment of springs, an operation that is sometimes called "flashing." This name is derived from the ignition of the oil that remains on the surface of the steel shortly after removing from the bath. The time required in the bath may be determined by the speed with which ignition takes place after the steel is removed from the bath, but it is better practice to quench for a definite period of time.

Time Quenching Thin Sections for Straightening.—The results of time quenching depend, to a considerable degree, upon the size of the piece being quenched. Large pieces can be removed from the bath with a considerable amount of residual heat so that drawing is possible. Small pieces, on the other hand, cool quickly so that it may not be possible to draw by time quenching. But time quenching is used with thin sections for a purpose that has nothing to do with drawing. If thin parts are removed from the quenching bath while hot, at a temperature that has not been measured but is probably about 500° F., they can be easily bent or straightened without breakage while they are hot. On cooling, such parts will suddenly become hard and brittle. The probable explanation of this peculiar phenomenon is that the softer and more ductile austenite is formed at first but is later transformed into martensite, which is hard and brittle.

Knowledge of this transformation was once a part of tricks of the trade, although the reason for it was not known. Thin saws have long been straightened while still ductile after quenching. Very thin parts are quenched in oil because this is sufficiently drastic. On the other hand, parts of heavier section require more drastic quenching. Plowshares and mould boards are quenched in iced brine, removed from the bath while still hot, and then straightened in a press that is quickly lowered into a tank of cold water for the final cooling. These parts are usually $\frac{1}{4}$ in. thick but vary between $\frac{3}{16}$ and $\frac{3}{8}$ in.

Controlling Distortion.—Control of distortion is not always so simple, and as such control is often of importance, various methods have been devised for preventing or removing distortion due to quenching. Expensive tools and accurately formed parts can be ruined by distortion, for which heating as well as

quenching, may be responsible. If the distortion is not partly due to an irregular shape, a special steel that can be properly hardened in a comparatively slowly cooling quenching medium may be used, distortion being reduced by less drastic quenching. Distortion is quite commonly controlled by mechanical devices that hold the piece being quenched and thus prevent change of shape. Flat spring leaves are frequently quenched in a quenching machine, and such machines are built for the hardening of gears and other parts of similar shape. An example of a quenching machine for gears is shown in Fig. 24. Another method

FIG. 24.—Hardening machines.

for control of distortion neglects the distortion, the part being ground to shape after hardening, a method that is applicable to small, flat pieces.

Modifying Hardness.—When physical properties that require a combination of hardness and toughness are desired, the common method of treatment includes quenching followed by drawing. The quench is made sufficiently drastic to allow for subsequent softening by reheating. The physical properties desired are obtained by drawing, and such properties can be varied by varying the drawing temperature. In such treatment, the quenching temperature is practically fixed, but the results may be further varied by using different quenching mediums.

For example, the drawing temperatures required for definite combinations of physical properties will be lower if oil is the quenching medium than if water is used for quenching, oil being less drastic.

Quenching for Physical Properties in Selected Medium.—By the use of selected quenching mediums, this variation in drawing temperatures may be carried to a point where drawing may be entirely eliminated, and the properties desired obtained by quenching alone. For such treatment, the heavy oils and greases are commonly used, although the selection of the medium depends upon the size of the piece to be treated. Very small, thin parts are often treated in this way, not only to avoid a subsequent draw but also for results not easily obtained by quenching and drawing. For example, small, sharp-pointed gravers, for marking on steel, are commonly quenched in soap. This method of treatment has some commercial importance but has not been given a specific name. To treatment in a selected quenching medium that did not include a subsequent draw the term "tempering" was once commonly applied. Later, this term was also applied to hardening and drawing but is now applied only to drawing.

Patenting.—In the wire industry, molten lead is employed as a quenching medium when increased tensile strength is desired. Annealing between operations removes nearly all the tensile strength gained by the cold working of wire drawing, but if heat treatment by quenching in molten lead, a process called "patenting," replaces annealing, the tensile strength can be considerably increased. The structure that results is sorbitic, presuming carbon steel to be employed, the common material for wire. Patenting is a process of long standing. Wire that has a carbon segregation in the center often breaks under the pull of wire drawing, but if such wire is patented, breakage will rarely occur. The structure is homogeneous. The following table[1] illustrates the comparative results of annealing and patenting.

[1] From a very interesting paper by J. F. Tinsley read before the Amer. Iron Steel Inst., May, 1914.

PHYSICAL PROPERTIES ON COLD DRAWING AND ANNEALING 0.10 PER CENT CARBON-STEEL WIRE

Physical properties	Green rod 0.207 in.	First draft	Third draft	Process annealed	First draft	Third draft	Fifth draft	Process annealed	First draft	Third draft	Fifth draft	Seventh draft	Annealed	Dead soft
Per cent reduction of area by drawing	0	47	82	0	35	70	85	0	21	62	80.5	88.5	0	0
Tensile strength, pounds per square inch	68,000	113,000	150,000	60,000	93,000	130,000	145,000	62,500	82,000	124,000	143,000	151,500	68,000	50,000
Per cent elongation, in 10 in	25	2.5	1.5	30	3	2	1.5	28	3.5	2	1.5	1	25	32

PHYSICAL PROPERTIES ON COLD DRAWING AND PATENTING 0.50 CARBON-STEEL WIRE

Annealing at first patenting stage gave tensile strength 70,000; elongation 18 per cent

Physical properties	Green rod 0.207 in.	First draft	Second draft	Patented	First draft	Third draft	Fourth draft	Patented	First draft	Third draft	Fourth draft	Patented	First draft	Third draft
Reduction of area by drawing, per cent	0	28.5	51	0	30	50.5	65	0	30	66	76	0	30	66
Tensile strength, pounds per square inch	95,000	122,000	146,000	115,000	143,000	163,000	176,000	128,000	156,000	190,000	208,000	156,000	184,000	218,000
Elongation per cent in 10 in	10	2.9	2.8	8.2	2.8	2.7	2.6	7.8	2.0	1.9	1.8	6.0	2.0	1.9

Importance of Quenching Operation.—The wide range of results that can be obtained by varying the rate of cooling makes quenching perhaps the most important operation in heat treatment, yet it is an operation that has received comparatively little attention. Much has been written about critical points and heating, but only occasionally does quenching receive similar attention and then usually in connection with the different types of quenching mediums. Upon quenching methods has depended the trade of the skilled hardener, and the tricks of the trade are largely concerned with quenching. To this is, perhaps, due some of the neglect of the art, for secrecy is still not unknown. But every trick depends upon one or more of the principles that have been discussed—in final analysis, upon regulation of the rate of cooling. Volumes could be written on the many applications of these principles, but in the average plant methods of handling the liquid quenching mediums of commercial practice are of most interest and will be briefly discussed.

Quenching Equipment. Still and Circulating Baths.—Methods of handling the principal commercial quenching mediums—oil and water—will depend, to a large degree, on the type of work to be treated and the results required. When a very rapid rate of cooling is not required, it is common practice to use simple open containers, tanks, without other equipment. If the amount of steel to be quenched is large and if oil is used, it will become necessary to provide some means of cooling the oil to avoid overheating and the accompanying danger of fire. If the tanks are small, cooling may be obtained by surrounding the tank with a jacket through which flows cold water, but circulation is preferable. If heavy oil that becomes nearly solid at ordinary temperatures is used, it may be necessary to supply steam coils so that the oil may be heated and liquefied.

Circulating and Cooling Water and Oil for Quenching.—The still tank plays a considerable part in heat treatment, but in average practice circulation of the quenching medium is necessary not only to avoid overheating but also to maintain the bath within definite temperature limits. In some heat-treatment processes—hardening, for example—it will often be necesssary to circulate the oil or water at a much greater rate than that required for maintenance of uniform temperature in order to obtain maximum hardness and to avoid vapor pockets for reasons already explained.

In a circulating system, the quenching oil, being costly, is kept in storage tanks from which it is pumped through the quenching system of pipes and tanks, and to which it returns after passing through the system and a cooler. Water, on the other hand, is cheap and so, unless used in large quantities, passes through the quenching system to the sewer or is, perhaps, diverted to the boilers or used for other purposes. When the cost is high and if water from the quenching system cannot be used economically for other purposes, a cooling system is usually provided to allow recirculation. Water is cooled most economically by exposure, in a thin layer, to air, and a cooling system for water is usually composed of simple baffle plates of wood or galvanized iron over which it can flow in a thin stream, dripping from one row of baffles to another. Sometimes a series of shallow pans is used, one pan being placed above another, each pan having small perforations in the bottom through which the water can drip.

A similar cooling system is sometimes used for oil when no great quantity is required, but if much oil is circulated, especially at a fairly high temperature, such a system may be cumbersome. More efficient cooling can be obtained by bringing the oil into contact with pipes, or their equivalent, that contain running water. There are two types of oil coolers that depend on running water; in one, the oil lines pass through the water; in the other, the water lines pass through the oil. The first system has one advantage over the second in that leaks may be more easily observed; oil in the water can be easily seen. In the other system, water may enter the oil and be unnoticed until a cause of trouble. The first system is more generally used.

Oil coolers are ordinarily nothing more than open tanks through which water can flow, pipe lines for the circulation of the oil passing through the tank, as illustrated in Fig. 26. Such a tank may be of wood or, better, sheet steel. Through this tank pass the pipes for carrying oil. These pipes are arranged in parallel, each row of pipe being joined in a common header at each end. This arrangement in parallel is more efficient than a continuous pipe because the oil will flow more easily and because a larger amount of the hot oil comes in contact with the cooling surface. Heat transfer is more rapid from the hot oil as it leaves the tank, and the greater efficiency of the parallel system is due to this.

The open-tank system illustrated can be built at small expense, one advantage over more elaborate coolers. In cold weather,

a flow of water is usually unnecessary if the tank is placed outside the building. If placed inside, the space required may be a disadvantage in a plant that has a limited floor space, and for this reason closed tanks are sometimes used. A closed cylindrical tank may be placed vertically, so that the least floor space will be required, and can often be located in places where no open tank could go. If ample space is available, there is usually no advantage in using the closed tank. Floor space may also be saved by placing the cooling tank outside the building, as indicated in the illustration.

Piping Systems.—The piping and pumping systems used for quenching oil are practically the same as those used for fuel oil. There is little difference in the handling requirements except that fuel oil usually requires heating before use, and quenching oil is

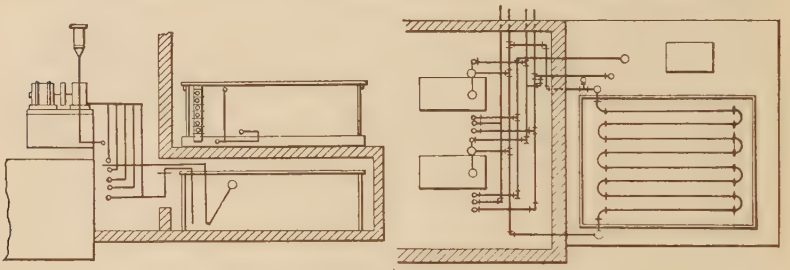


FIG. 25.—Quenching oil cooling and circulating system.

generally cooled after service. Quenching oil may be drawn from and return to the storage tank or a sump may be used, as suggested for fuel oil, filled from the storage tank as required. A sump is of service in removing dirt from the oil and makes the system more compact. When a sump is used, a change may be easily made from one kind of quenching oil to another, sometimes an advantage when the production is varied. In Fig. 25 is also shown a piping system and tank for quenching oil with duplicate pumps. The pumps are located within the building, the sump (or storage tank), just outside.

Quenching Tanks. Stationary Tanks. Car Tank.—The object of this piping and delivery system is to bring the quenching medium to the quenching tank in which the work in process is to be cooled. Quenching tanks vary in kind, size, and shape according to the process and the parts to be handled. In general, there are two kinds, stationary and movable, the stationary tank being used in most heat-treatment plants.

Stationary tanks may be placed directly against the front of the furnace, at floor level or hearth level, as illustrated in Fig. 26; or at a little distance from the furnace, as shown in Figs. 27 and 28; or they may be placed at some distance from the furnaces. The top of the tank may be at or close to the level of the hearth or may be at floor level: location depends on the space available and on the method of handling parts.

The arrangement illustrated in Fig. 27 is convenient for parts of moderate size. Oil and water are carried in alternate tanks.

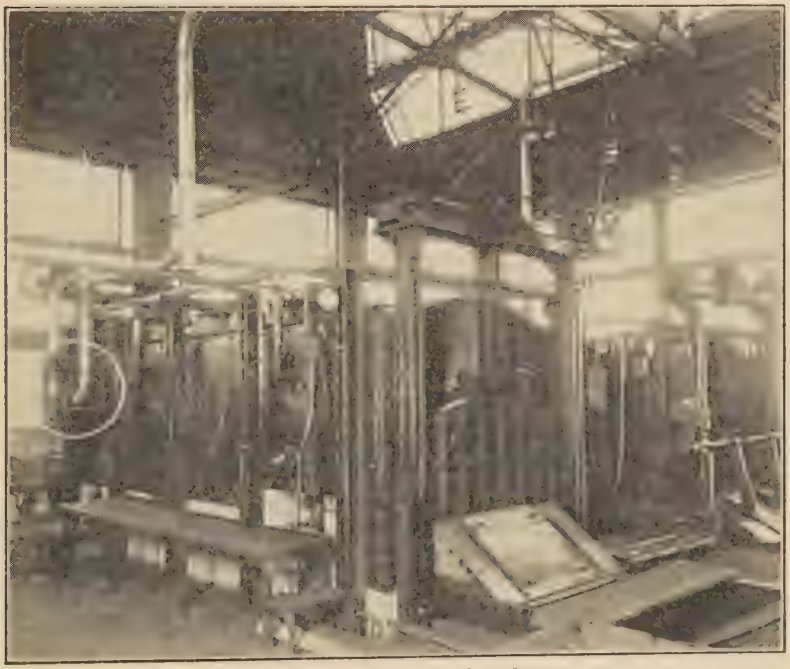


FIG. 26.—Floor level tank.

With the tanks at a little distance from the furnace it is possible to place the burners at the front and the furnace and tank are entirely accessible. The piping is carried in a trench, following the arrangement shown in Figs. 168 and 169 (Chap. XV). All the advantage of having the tank close to the furnace can be gained by the addition of removable plates extending from the hearth door to the tank, as in Fig. 26.

Such close proximity to the furnace necessarily means a comparatively small tank. When large tanks are required, it may

be necessary to place them at some distance. The large tank may be necessary for large parts or, perhaps, in quenching from

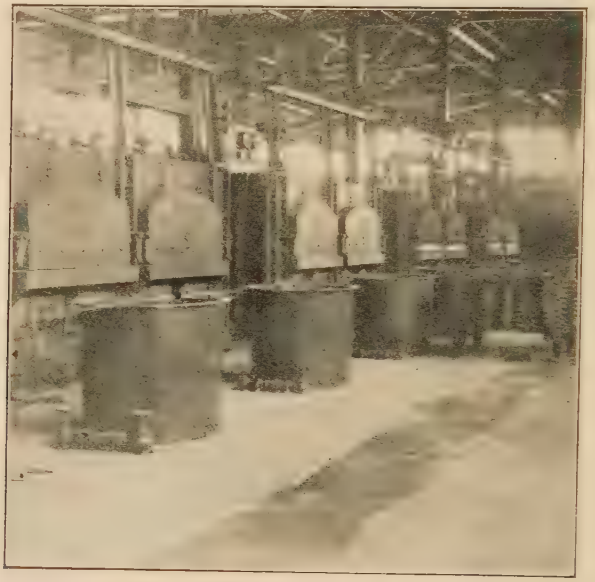


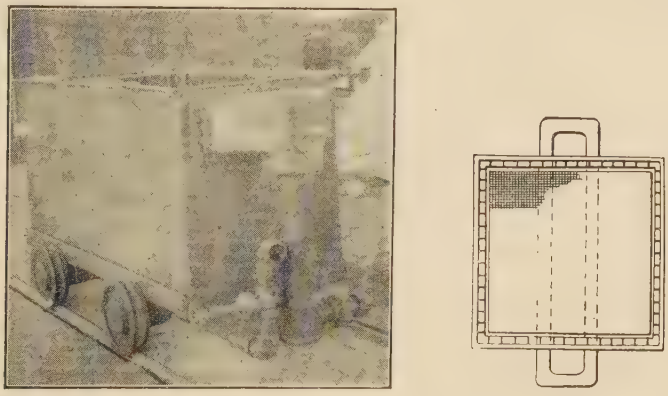
FIG. 27.—Stationary quenching tanks.

FIG. 28.—Quenching tanks.

carburizing, a process to be described. To bring the large tank in close proximity to the furnace so that there will be no interference in handling and no loss of valuable floor space, movable

tanks have been developed, the type commonly used being called a "car tank." An example is shown in Fig. 29 (*a*) and, also, in Fig. 173. Figure 29 (*b*) illustrates a basket used with this car tank. By means of a track that runs close to the row of furnaces, the car tank can be placed close to any furnace. Pipe lines, with connections at convenient intervals for intake and outlet, can be carried in a trench below floor level, as described, or the intake lines can be brought down from above.

In order to keep any tank full, it is necessary to place the intake at the bottom and the outlet at the top, a convenient necessity in that the hot liquid at the top will be removed quickly. Pipe lines may be brought into or from tanks through pipe flanges



(*a*) (*b*)

FIG. 29.—(*a*) Car tank, (*b*) screen for quenching tank.

fastened to the tank, or headers may be used, as illustrated in Fig. 29 (*a*). A tank that is filled from the bottom, with overflow at the top, is not easily emptied for cleaning or repair. To permit emptying, a bypass should run from the intake to the outlet line as illustrated in Fig. 27, two valves being required.

The size of the inlet and outlet pipes for the quenching tank has an important bearing on results, especially in hardening. Pipe lines should be large enough to give the flow desired. When a rapid flow of medium is necessary, the average tank should be supplied through a 2-in. pipe, presuming water pressure of 60 to 65 lb. or an oil pressure of 35 to 40 lb. The outlet should have at least three times the area of the inlet pipe. With the flow thus provided, heat treatment can be carried on with little trouble from quenching.

CHAPTER V

ANNEALING

Annealing and Its Objects.—"Annealing" is a general term employed for processes of heating and cooling that have objects other than hardening for service. The principal objects of annealing are

Machinability.
Ductility.
Refinement of the crystalline structure.

Other objects are sometimes included, for example altering magnetic or electrical properties, but the three given are the most important objects of steel-treating practice. Baking processes are sometimes included, for example the baking of steel after pickling to remove hydrogen taken up by the steel from the pickling bath, steel in this condition being brittle. The hydrogen will depart in a few hours, but baking hastens the process. In practice, this treatment is not considered to be annealing. In wire drawing, for example, baking and annealing are distinctly separate processes.

The use of this one term "annealing" to cover processes that have such different objects is due to a lack of definite knowledge in early practice of the results of specific treatments and, also, to a lack of definite standards by which physical properties can be measured. In general, only two results of heat treatment were then recognized, namely, hardening and softening. That refinement of the crystalline structure could also be obtained was also recognized but as a general result of the processes rather than as a specific object. This was partly due to the fact that refining was a result of hardening as well as of softening. The term "annealing" implied softening as opposed to hardening. Then no standards existed by which the term "soft" could be exactly defined when applied to steel; now softness implies a low elastic limit accompanied by high ductility, a combination that provides toughness. These properties can

be easily defined by exact physical standards. Without these standards, the individual properties can easily be confused. For example, the early steel treater recognized soft steel by the ease with which he could bend or otherwise deform a bar or strip. *Dead soft* steel in a comparatively thin strip could be bent in the hands without difficulty, but harder steel required more effort. Such a test provided a rough means of determining the elastic limit. A steel that was easily deformed was also usually ductile and tough. But the elastic limit is lowered with an increase in grain size. Other conditions being the same, the steel treater could bend a strip of coarse-grained steel more easily than a similar strip of fine-grained steel. That the softer steel would be more brittle was contrary to his usual experience. According to his standard, a strip that could be bent easily might well be preferred to one that could not be bent so easily. Similar misunderstandings were once common.

The three principal objects of annealing—machinability, ductility, refining—may be gained by one process if the temperature of heating is slightly above the critical range, and the rate of subsequent cooling sufficiently slow. Furthermore, an annealing process may increase machinability by increase of ductility but, under other conditions, may decrease machinability by increasing the ductility. For example, a high-carbon steel, after annealing, may be both ductile and machinable, but a low-carbon steel that is made as ductile as possible cannot be easily machined. The use of the one term "annealing" for several processes that have widely different results and objects is responsible for much confusion. The differences in structure and in physical properties obtained by the different processes of annealing are better recognized, however, and new terms have been devised to distinguished them, although only two processes have been thus distinguished. The basis of annealing processes is a change of structure to that most suitable for the object desired, and the particular treatment employed will depend largely upon the composition of the steel.

Annealing for Machinability.—Heat treatment for machinability depends almost entirely upon the composition of the steel, although the processes employed are sometimes apparently alike for steels of different type. Machinability is determined by structure, and the particular structure required will differ with different types of steel. For example, of the plain carbon steels,

low-carbon steel is too soft for machinability and is, therefore, hardened. Medium-carbon steel is usually machinable as rolled and is, therefore, rarely treated to improve machinability. High-carbon steel, tool steel, is annealed to soften. Low-carbon, low-alloy steels are usually hardened for machinability, but the higher-alloy steels require softening, particularly if the carbon is high. The structure desired, however, is not that obtained by annealing the high-carbon carbon steels. Carbon and alloy content determine the process to employ.

Machinability in Carbon Steel, Low and Medium.—Carbon steel in the low-carbon range, 0.10 to 0.20 per cent, is not annealed for machinability but is hardened by quenching in water. The hardness thus obtained is not great but can be considerably increased by drastic quenching. Such steel, however, in the form of rod is usually hardened by cold drawing, because better results can be obtained by this method and at less expense than heat treatment would require. If the carbon content lies between 0.20 and 0.30, quenching will usually be followed by drawing to the hardness desired. Carbon steel containing between 0.30 and 0.60 per cent of carbon seldom requires annealing for machinability after forging or rolling. If necessary, such steel will usually be quenched and drawn, using either oil or water as the quenching medium, water being preferred for the low end of the range given.

Machinability in High-carbon Steel. Spheroidizing.—Carbon steels containing 0.75 per cent or more carbon are annealed for machinability. The object of annealing is a change in the structure of the pearlite. Lamellar pearlite, as illustrated in Fig. 8 and other photomicrographs, is composed of alternate layers of ferrite and cementite. The cementite being exceedingly hard, quickly wears a cutting tool. The layers can be broken up by treatment with the formation of globules or spheroids of cementite. This structure, called "spheroidized" or "globular pearlite," can be formed by cooling very slowly through the critical range, as in a furnace. Lamellar pearlite, moreover, once formed, can be converted into spheroidized by holding for some time at temperatures just below the critical range. The process may be hastened by repeated rise of temperature to points just within the critical range followed by cooling to temperatures just below this range. Spheroidized pearlite is shown in Fig. 30. This treatment is commonly known as "balling up"

the pearlite. A mixture of lamellar and spheroidized pearlite is sometimes desired for machinability and is obtained by regulating the time of cooling. This treatment can be applied to any carbon steel. The grain size resulting from slow cooling through the critical range is slightly larger than that resulting from more rapid cooling. For this reason, holding at temperatures just below the critical range is sometimes the preferred method. The temperature commonly employed is 1250° F. (675° C.).

Annealing Alloy Steel.—Alloy steels are treated for machinability by much the same methods as those applied to the plain carbon steels but not always for the same internal structures. Low-carbon alloy steels of the types represented by 2315, 2320 or 3115, 3120 are usually cold drawn for machinability. Cold-

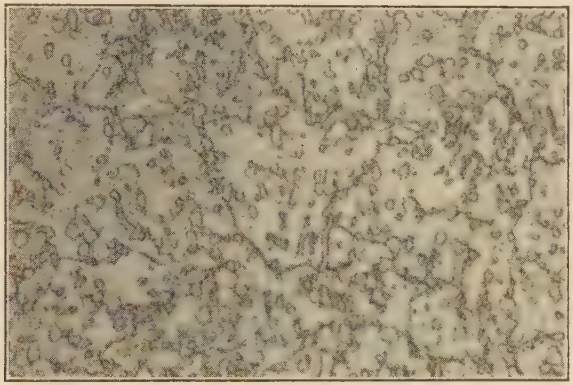


FIG. 30.—Globular or spheroidized pearlite. 0.84 carbon tool-steel heated to 1450° F. (790° C.), cooled slowly in furnace. 1000 diameters.

drawn 2320 finds service in studs and bolts. If heat treatment is required for machinability, these steels are usually quenched and drawn although sometimes annealed by heating to temperatures above the critical range followed by air cooling. The heat treatment of cold-drawn nickel steel for machinability is a common error, but heat treatment is required for shapes other than rod.

Alloy steels higher in carbon and alloying elements are usually annealed for machinability by the same processes that are applied to high-carbon steel for spheroidizing. They may be heated to temperatures slightly above the critical range and cooled slowly in the furnace or may be held at a temperature just below the critical range. The result, however, is not always spheroidized

pearlite. Alloy steels retain the solution structures more easily than the plain carbon steels and, therefore, may be sorbitic, troostitic, and even martensitic when cooled in air or at a slower rate, this depending upon the content of carbon and alloying elements. As this content increases, pearlite is obtained with more difficulty. Sorbite rather than pearlite is sought in making steels with a high content of carbon and alloying elements machinable. Figure 31 illustrates the structure obtained by slowly cooling a 3150 steel through the critical range, a structure

FIG. 31.—Gear forging 3150 steel annealed 1450° F. (790° C.), slowly cooled. 500 diameters.

composed of both lamellar and spheroidized pearlite. Traces of sorbite may also remain.

Steels that are martensitic or troostitic after cooling in air are known as air-hardening steels. Such steel can be made sorbitic by heating to a temperature just below the critical range and cooling as desired or by heating to temperatures just within the critical range followed by slow cooling to temperatures just below. This is practically a drawing process and the method is known as a "quick anneal." Better results are obtained by slow cooling, as in a furnace, from temperatures slightly above the critical range.

Annealing High-speed Steel.—High-speed steel is a solid solution, and annealing, therefore, does not change the structure to such a marked degree. High-speed steel is softened for machinability by heating to 1550° F. (845° C.) and holding at temperature for from 1 to 4 hours, the time required depending upon the size of the piece. Heating is followed by slow cooling to 700° F. Thin sections are sometimes annealed by a shorter method that requires heating to 1300° F. (700° C.), cooling in the furnace to 700° F. (370° C.), followed by reheating to 1300° F. (700° C.) and cooling in air. The second heating may be omitted if the piece is small.

Annealing after Hardening by Cold Forming.—The term "annealing" is also applied to the softening—lowering the tensile

Fig. 32.—Cold-drawn steel—0.40 carbon. 125 diameters.

strength and increasing the ductility—of steel that has been cold worked, as in the industrial process of wire drawing, cold pressing (stamping), and cold rolling of sheet and strip. Cold forming hardens steel and elongates the crystals, as shown in Fig. 32. The deformation that is possible without fracture is limited, and when the limit is approached annealing is necessary before further deformation can be applied. Wire, for example, is cold drawn as much as possible without fracture occurring and is then annealed to remove the effect of the cold working. This is repeated until the desired size has been obtained. Other processes of cold working are carried on in the same way. The effect of cold work is removed by heating, but this treatment is not connected with the critical temperatures. Softening

begins when the temperature of the cold-drawn steel is raised to about 500° F. (260° C.), but maximum softness requires heating to about 1300° F. (700° C.). Some cold working operations occasionally require heating to higher temperatures, but 1250° F. (675° C.) is a standard temperature in industry for annealing after cold working. Holding at temperature is unnecessary, although time should be allowed for reaching the required temperature throughout a large piece or mass.

Hardening by cold working is often a result of machining, particularly if the cutting tool is dull. The surface hardness of low-carbon steel can be increased from 20 to 60 or more on the scleroscope scale as a result of the pressure of a dull lathe tool. The surface is glazed, and cutting becomes difficult, if not impossible, unless the tool can get below the hardened layer. The increased hardness that results from machining is partly responsible for an opinion that steel contains hard spots, a natural conclusion if the hardening effect of machining is not realized. Once the surface has been so hardened, annealing becomes necessary. This surface hardness is sometimes responsible for distortion on subsequent heating, and machining is, therefore, sometimes followed by annealing at 1000 to 1200° F. (540 to 650° C.). Such treatment, however, is not common practice. Annealing operations have been extensively applied because of the hardening effect of machining, the cause of the difficulty not being known.

Annealing to Refine the Crystalline Structure.—Another object of annealing, the refinement of the crystalline structure (or grain refining), depends upon the recrystallization of steel on heating to a temperature slightly above the A_{c3} point (or A_{c3-2-1}). The rate of subsequent cooling has a comparatively slight effect upon the resulting grain size, although this will be smaller if the rate of cooling is rapid than if slow. Annealing for refinement requires heating to a temperature slightly above the A_{c3} point, followed, ordinarily, by cooling in air or at a slower rate, if some other object is also desired, for example better machinability. One exception to such heating will be mentioned. For lack of a better term, this treatment will be called "annealing for grain refining" or, simply, "grain refining."

Grain refining is a toughening treatment. Refinement results in an increase in the elastic limit and tensile strength and in the ductility as well. Coarse-grained steel is more brittle than fine-

grained steel. Improving the physical properties, however, is not the only object of such treatment. A change in the size of the crystals of steel is usually accompanied by a change of shape, distortion. An expensive tool machined from a coarse-grained bar of steel may be ruined by distortion on hardening due to the refinement that takes place. A refining treatment may, therefore, precede machining. Such treatment may include either slow or rapid cooling and be either an annealing or a hardening treatment. If hardening, an annealing treatment will follow.

Inasmuch as refining requires heating to temperatures slightly above the critical range, annealing and hardening temperatures are the same. Refining temperatures are represented by the A_{c3} point or the A_{c3-2} or the A_{c3-2-1} point. Steels composed entirely of pearlite (eutectoid steels) and steels containing pearlite and excess cementite (hypereutectoid steels) are all refined in the same range of temperature. If, however, the excess cementite of hypereutectoid steel entirely surrounds the grains, refining will require heating to temperatures above the A_{ccm} point followed by heating to temperatures just above the A_{c3-2-1} point. This additional treatment is preliminary to the final refining treatment.

Normalizing.—Annealing for grain refining (and hardening) will result in a small crystal size, provided that the size of the crystals in the steel to be treated is not too great and if any excess cementite does not surround the grains. If, however, the crystals are of large size or surrounded by cementite, ordinary refining treatment (heating to temperatures just above the critical range) will have little or no effect. The method of dealing with the excess cementite has been mentioned, but crystals of large size may require heating to temperatures well above the critical range, a treatment that so decreases the grain size that subsequent refining will be complete. Such treatment is known as "normalizing" and may include cooling in air or at a slower rate or a quench, although this will not be for the purpose of hardening but rather to obtain a grain size somewhat smaller than that resulting from a slower rate of cooling.

The term "normalizing," implying making normal for further treatment, is applied to a large number of processes radically different in result and is also applied to processes that have been described here as grain refining. As a result, considerable mis-

understanding exists. A separate normalizing treatment is seldom required for steel of very low-carbon content because of the high temperature of the A_{r3} point. Normalizing and refining temperatures are the same. For the hypereutectoid steels, the temperatures of the A_{ccm} point is also high, but this is a normalizing rather than a final refining temperature. The term was first applied in this country to the preliminary treatment just described and is confined to that here for that reason.

Normalizing is based on heating rather than on cooling. Air cooling is usually specified; hence, the inclusion of normalizing in annealing processes; but heating may also be followed by quenching. Such quenching, however, is not for the purpose of hardening but rather as an aid in reducing the crystal size. The process is, perhaps, best illustrated by specifications that include this treatment. Specification might read

Normalize at 1600° F. (870° C.).
Harden at 1425° F. (775° C.).

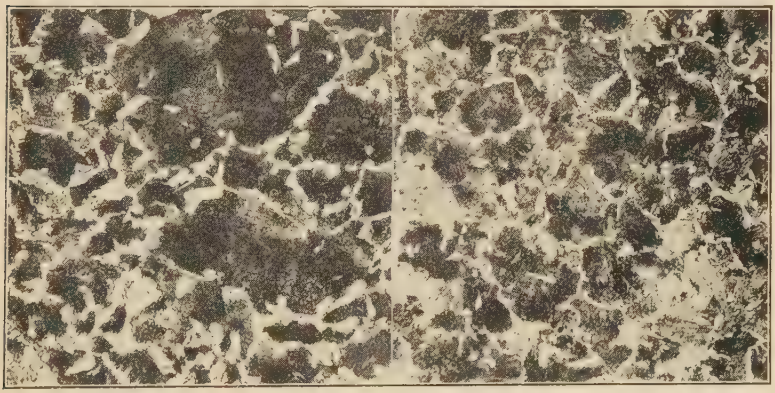
Specification for industrial purposes would be more definite:

Heat to 1600° F. (870° C.).
Cool in air (or quench in oil).
Reheat to 1425° F. (775° C.).
Cool slowly in furnace.
Machine.
Heat to 1425° F. (775° C.).
Quench in oil.

In this process, 1600° F. (870° C.) is the normalizing temperature, 1425° F. (775° C.) is the refining or hardening temperature. Slow cooling in the furnace is required for machinability, an annealing operation.

Normalizing as described, is necessary only if overheating has occurred and may, therefore, be avoided if overheating is prevented. In industrial practice, more attention is being given to controlling temperatures in such processes as forging and hot rolling. In such processes, the size of the crystals of steel is reduced by the mechanical work performed, and the final size depends on the finishing temperature. In hot rolling, it is sometimes possible to control the finishing temperature without much reference to the temperature of heating at the start. More often, however, finishing temperatures will depend upon the temperature to which the steel has been heated origi-

nally, a statement that is particularly true in forging. Sometimes, overheating has reached a temperature so high that, particularly in large pieces, even a normalizing operation will not completely remove the effect. The suggestion has been made that such steel be given several normalizing treatments. Theoretically this may do, but practically such operations are expensive and not always satisfactory. It is far more satisfactory and much less costly to prevent overheating than to add a normalizing operation to remove the effects. The results of treatments for normalizing and grain refining are illustrated in Fig. 33. The effect of mechanical work on grain size may be noted in series *A*.

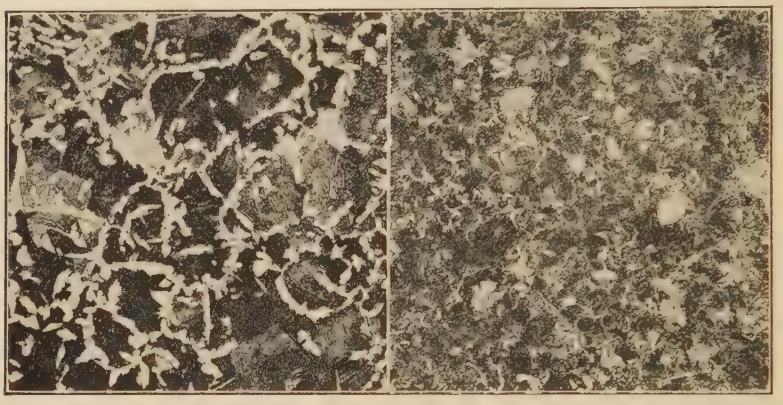


(*a*) (*b*)

Fig. 33.—Series *A*. Illustrating effect of forging, normalizing and heat treating. 1055 steel. Carbon (*a*) Rolled 0.55. 100 diameters (*b*) forged.

Annealing Steel Castings. Ingotism.—The crystalline structure of cast metal is naturally very coarse, and cast steel is, therefore, not easily refined except by mechanical work (rolling or forging, for example). Because of the presence of exceedingly large grains, steel ingots sometimes crumble in rolling. The coarsely crystalline structure formed on casting steel is known as "ingotism." This structure is very persistent, and traces may be noted in rolled or forged steel. Steel castings do not receive mechanical work but are refined by annealing at temperatures above the critical range. To break up ingotism in steel castings requires time, and they are, therefore, held in the annealing furnace for several hours. Some operators prefer to heat to temperatures not far above the critical range. Others

prefer higher temperatures, the treatment being normalizing, perhaps, rather than refining. A representative treatment that



(*c*) (*d*)

(*e*)

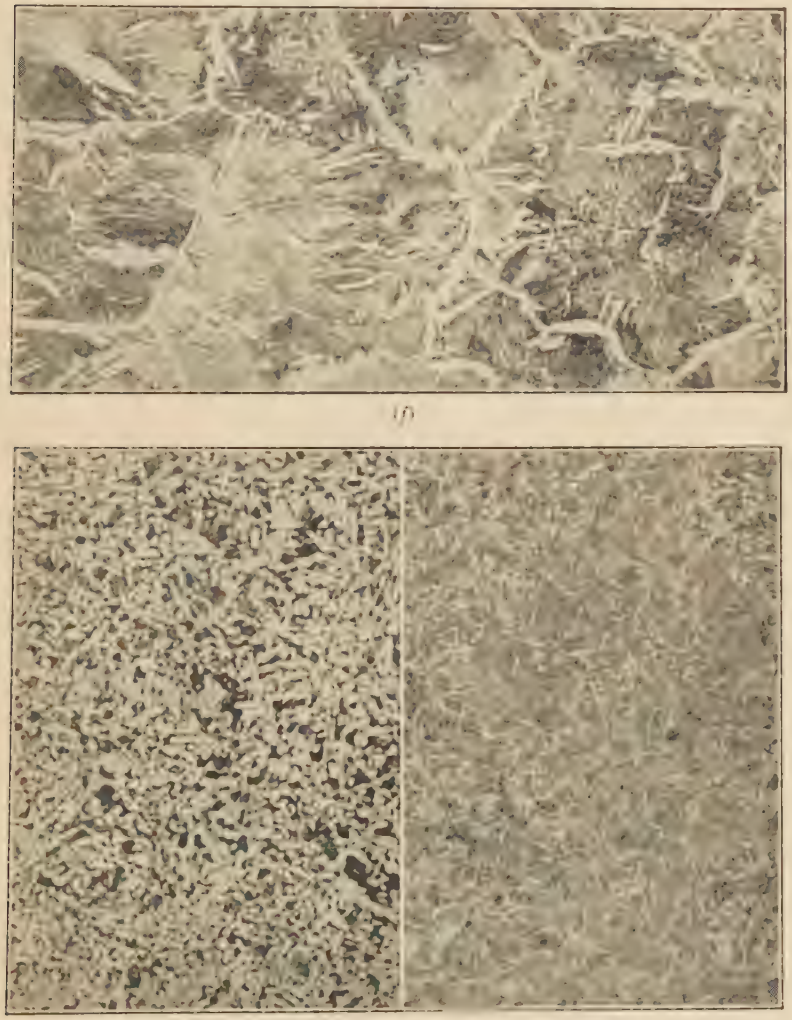
FIG. 33.—Series *A* (*Continued*). (*c*) Normalized 1600° F. (870° C.). 100 diameters. (*d*) quenched 1500° F. (815° C.) drawn 1100° F. (595° C.). 100 diameters. (*e*) annealed 1500° F. (815° C.). 125 diameters.

calls for heating to temperatures not much above the critical range is as follows:

Heat to 1625° F. (885° C.).
Hold for time required.
Cool in air (or in furnace).
[1]Reheat to 1540° F. (840° C.).
Hold for time required.
Cool in air.

[1]Second heating sometimes omitted.

The time required at temperature depends upon the size of section. Castings 4 in. thick, for example, are held for 16 hours



(*f*) (*g*) (*h*)

FIG. 33 (*Continued*).—Series *B*. 0.30 carbon steel. 100 diameters. (*f*) Forged, (*g*) heated to 1550° F. (846° C.) air cooled, (*h*) quenched 1550° F. (845° C.), drawn 1100° F. (595° C.).

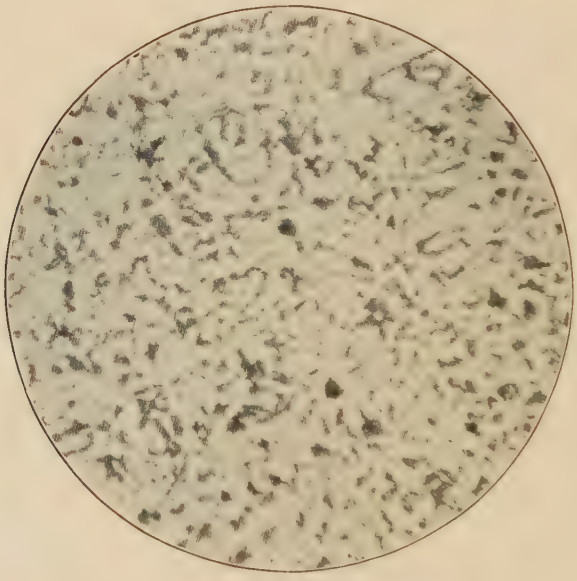
on the first heat and for 8 hours on the second. Representative physical properties of a 0.35 per cent carbon-steel casting after such treatments are

Yield point, pounds per square inch	37,000
Tensile strength, pounds per square inch	77,000
Elongation in 2 in., per cent	24.5
Reduction of area, per cent	39

Occasionally, greater ductility is desirable, and the treatment given is followed by heating to and holding at 1290° F. (700° C.) for spheroidizing. Typical physical properties of 0.30 per cent carbon-steel casting after spheroidizing are

Yield point, pounds per square inch	34,500	36,900	34,800
Tensile strength, pounds per square inch	77,900	67,200	65,500
Elongation in 2 in., per cent	34	32	34.5
Reduction of area, per cent	56	53	64

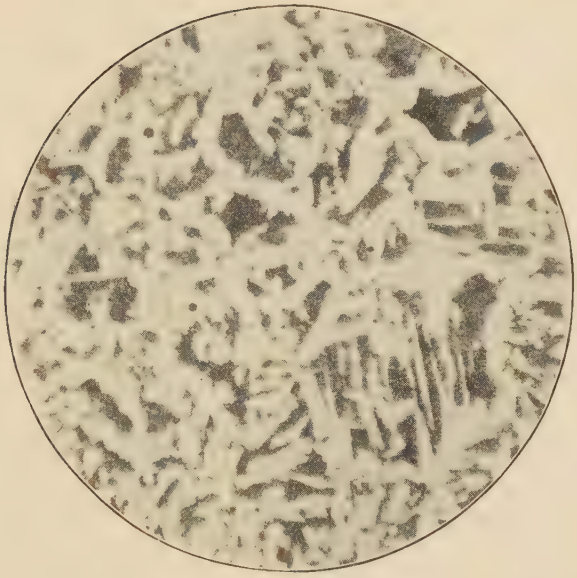
The typical structure is shown in Fig. 34 (*a*).



(*a*)

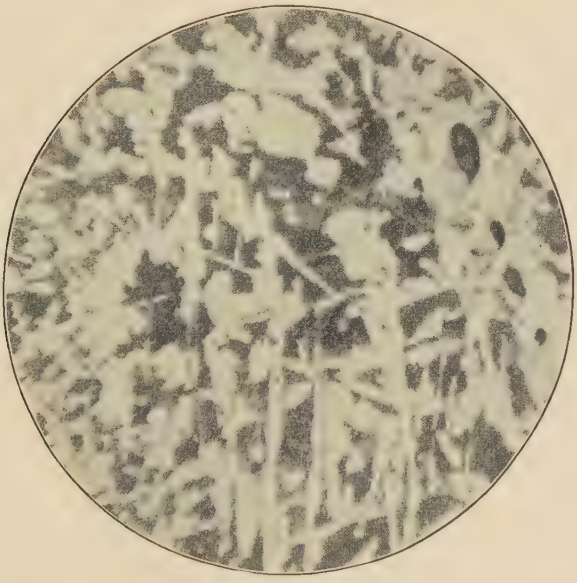
FIG. 34.—(*a*) Steel casting. Annealed and spheroidized. 100 diameters.

Some operators prefer higher annealing temperatures, recommending 1650 to 1700° F. (900 to 925° C.) for small castings and 1850 to 1900° F. (1010 to 1040° C.) for large castings. The higher temperatures shorten the time required but are responsible for rapid deterioration of the furnace.



(*b*)

FIG. 34 (*Continued*).—(*b*) Annealed steel casting. Illustrating persistence of ingotism. 100 diameters.



(*c*)

FIG. 34 (*Continued*).—(*c*) Heat treated steel forging. Illustrating persistence of ingotism. 100 diameters.

Castings are sometimes heat treated (quenched and drawn), often after annealing, as an aid in refining. This, however, is not common practice and is generally avoided because annealing is sufficient for refining and, also, because of the danger of cracking the casting by quenching, particularly if the shape is irregular.

The persistance of ingotism is illustrated in Fig. 33, series *B*, in the photomicrograph of 0.30 per cent carbon steel heated to 1550° F. and air cooled. Slight traces of the coarse grained structure can be seen. Better illustrations are shown in Fig. 34 (*b*) and (*c*). The outline of the original grain structure in an annealed steel casting is shown in Fig. 34 (*b*). Figure 34 (*c*) illustrates the persistence of the coarse structure after overheating a steel forging. The outlines of large crystals, usually triangular shape, can be easily detected in both pictures. Both castings and forging have been heat treated, the one by annealing, the other by quenching and drawing.

Grain Growth in Deformed and Annealed Low-carbon Steel.—Overheating—heating to temperatures far above the critical range—is responsible for the formation of grains of large size, but overheating is not responsible for the occurrence of all large grains found in steel. The grain size of low-carbon steel will be greatly increased by deformation (cold working) in moderate amount followed by annealing at temperatures as low as 1300° F. (705° C.), a phenomenon known as "grain growth." That grain growth occurs in low-carbon steel has been known for a long time, but the cause remained obscure until recently. Grain growth occurs in many pure metals and homogeneous alloys as a result of deformation followed by annealing. Iron is such a metal, and ferrite, if not pure iron, may be considered as a homogeneous alloy. Steel containing less than about 0.20 per cent of carbon contains so much ferrite that grain growth is easily produced, but as the carbon content increases above that amount, steel becomes a mechanical mixture rather than a homogeneous alloy, and grain growth will not occur after deformation and annealing. Figure 35 shows grain growth in the decarburized portion of a bar containing a little over 0.20 per cent carbon and, also, shows the effect of pearlite in suppressing grain growth. Figure 36 shows growth in a ghostline.

The temperature range within which annealing will produce grain growth in slightly deformed steel lies between 1290° and

1650° F. (700 to 900° C.), the critical range of *cooling*. Slight grain growth will occur at temperatures below this range as low as 1250° F. (675° C.), and some observers have stated that grain growth occurs to a slight amount on annealing at 1200° F. (650° C.), but such growth is very moderate and not to be compared with that obtained by heating within the critical

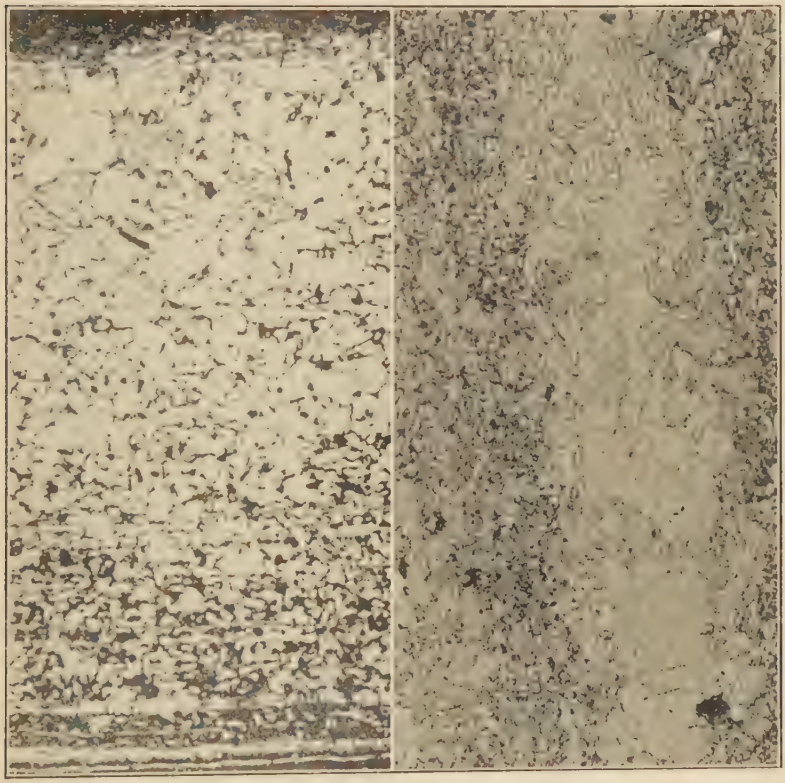


FIG. 35. FIG. 36.

FIG. 35.—Illustrating suppression of grain-growth by pearlite. 40 diameters.
FIG. 36.—Grain growth in ferrite band of hot-rolled sheet, 0.18 carbon. 100 diameters.

range of cooling and, furthermore, seems to occur under special conditions not yet completely explained. Ordinarily, little or no grain growth will occur on heating to temperatures below 1290° F. (700° C.), so that this temperature is a sharp dividing line. Under conditions that will be described, grain growth will not occur at temperatures above 1435° F. (780° C.), a temper-

ature that also marks a refining point; but under other conditions, this upper limit will be 1650° F. (900° C.), the A_{r3} point.

Grain growth on annealing has been responsible for serious difficulty in the manufacture and use of cold-drawn wire, pressings, hot- and cold-rolled strip, and sheet, rivets, and other products for which low-carbon steel is commonly used. In such cold-formed material, annealing within the range given may produce grain growth. The list of products includes hot-rolled sheet and strip, and the use of the term "cold formed" requires explanation. Grain growth is usually found in hot-rolled strip and sheet that is not too thin nor too thick, a statement purposely made indefinite because too many factors enter to permit giving exact sizes. This can be made more definite by the statement that grain growth is found most frequently in hot-rolled sheet and strip of finished thickness between $\frac{1}{8}$ and $\frac{1}{16}$ inch. Experiments indicate that deformation at temperatures up to 1435° F. followed by annealing will result in grain growth. Sheet or strip, comparatively thin, will cool quickly on rolling, so that the temperature at the last pass may be below 1435° F. (780° C.) but above 1290°F. (700° C.), and, therefore, grain-growth will result. Whether or not the finishing temperature falls within this range apparently depends, to a considerable extent, upon the gage to which the strip or sheet is finally rolled.

Limits within Which Deformation Can Produce Grain Growth. The amount of deformation—cold forming—that will produce grain growth is definitely limited. A very slight deformation, technically a load just above the elastic limit, followed by annealing as indicated will produce grains of large size. But as the deformation increases, the size of the grains produced by subsequent annealing will gradually decrease until no grain growth will occur. The range is so narrow that a satisfactory method of measuring this deformation, one that will cover all kinds of deformation, is not easily obtained. A process by which steel can be cold formed by gradual steps and by gradually increasing loads and that will also provide a method by which each step can be measured would permit a study of the conditions governing grain growth. To this ideal process wire drawing from hot-rolled rod is, perhaps, the nearest industrial process. Rod can be drawn into wire in steps as close together as 0.001 in., and the deformation can be measured by a very convenient standard, the reduction of area.

Grain Growth in Wire Drawing.—Wire drawing is no precise process by which exact measurement of deformation under all condition can be made, because hot-rolled rod is not always of uniform size and, also, because the deformation may be localized.

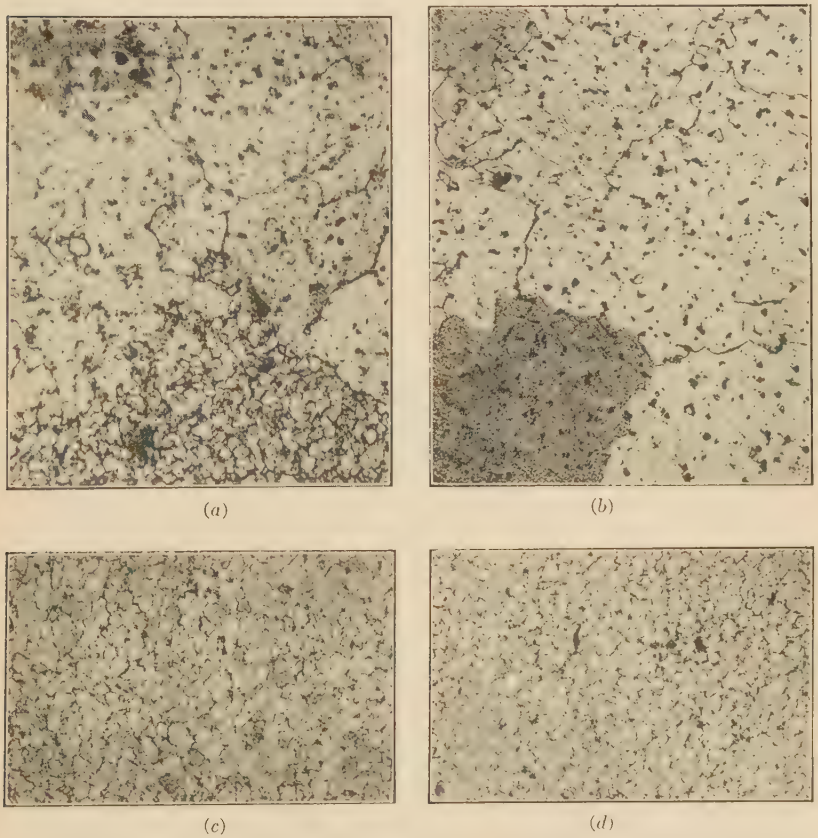


FIG. 37.—Illustrating effect of wire drawing and annealing on grain growth. 100 diameters. Reduced 33⅓ per cent. (*a*) 8 per cent reduction of area 1 hour at 1290° F. (700° C.), (*b*) 9 per cent reduction of area 1 hour at 1290° F. (700° C.), (*c*) above 8 per cent, reheated to 1450° F. (790° C.), (*d*) above 9 per cent, reheated to 1450° F. (790° C.).

When wire is drawn with a comparatively light draft, less than about 7 per cent reduction of area, only the outer portion may be affected. Here the deformation may be comparatively great, and no grain growth will occur on annealing. If the deformation covers a somewhat larger area, goes a little deeper, so that the

unit strain is less, grain growth on subsequent annealing will occur in a narrow ring close to the periphery of the wire. If, however, the draft is greater and the resulting reduction of area more than about 7 per cent, deformation will be comparatively

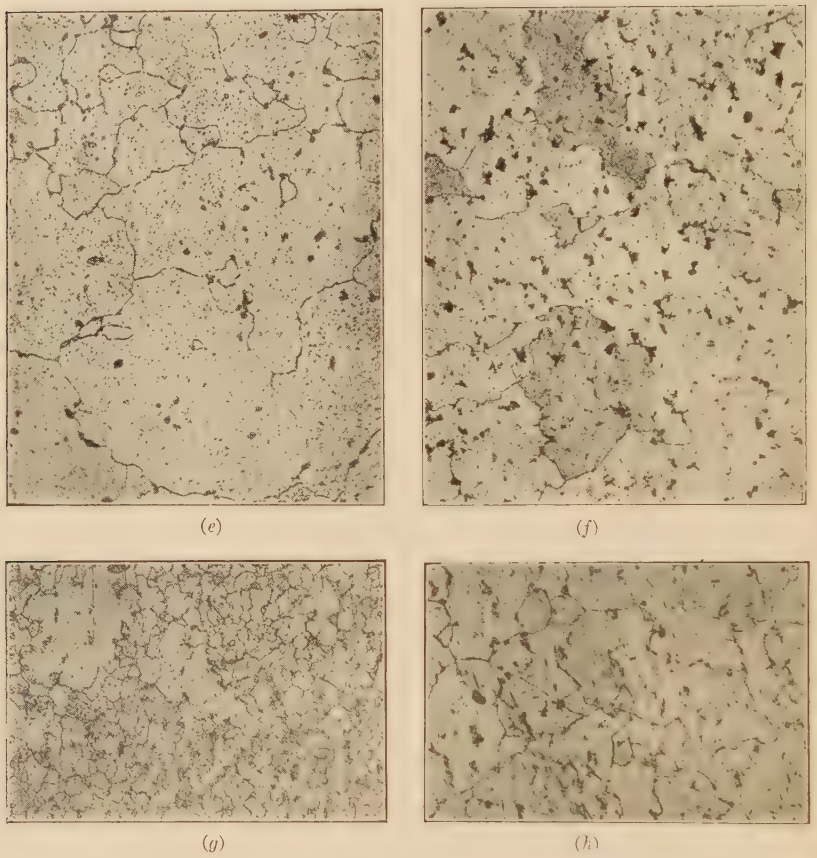
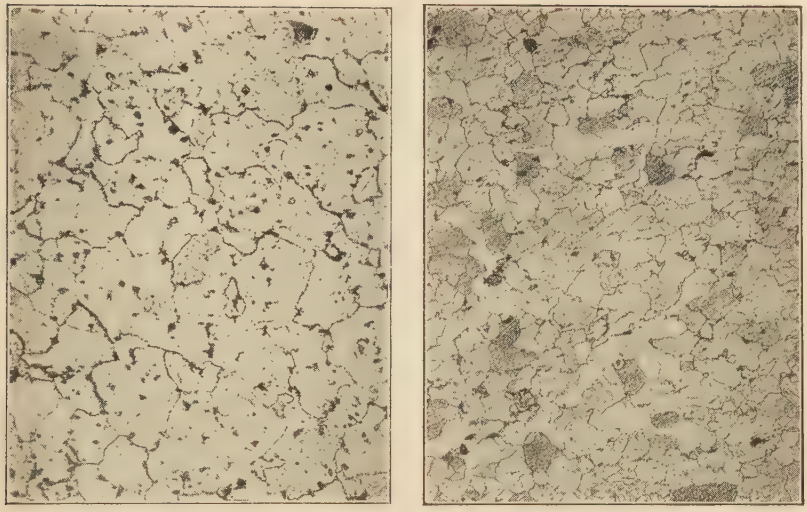


FIG. 37 (*Continued*).—Illustrating effect of wire drawing and annealing on grain growth. (*e*) 10 per cent reduction of area 1 hour at 1290° F. (700° C.), (*f*) 11 per cent reduction of area 1 hour at 1290° F. (700° C.), (*g*) above 10 per cent, reheated to 1450° F. (790° C.), (*h*) above 11 per cent, reheated to 1450° F. (790° C.).

uniform throughout the section, and the effect of increasing deformation can then be tested. The table on page 149 illustrates the effect of wire drawing with increasing reduction of area, results that are illustrated in the photographs of Fig. 37. Similar conditions will produce similar grain growth in cold-rolled strip.



(*i*) (*j*)

FIG. 37 (*Continued*).—Illustrating effect of wire drawing and annealing on grain growth. (*i*) 12.5 per cent reduction of area 1 hour at 1290° F. (700° C.) No change on heating to 1450° F. (790° C.). (*j*) 16 per cent reduction of area 1 hour at 1290° F. (700° C.). No change on heating to 1450° F. (790° C.).

GRAIN GROWTH RESULTING FROM DEFORMATION AND ANNEALING. ILLUSTRATED BY COLD DRAWING ROD 0.320 IN. IN DIAMETER WITH INCREASING REDUCTIONS OF AREA[1]

After Drawing

Diameter, inches	Reduction area, per cent	Grain size, millimeters, after 1 hour at	
		1290° F. (700° C.)	1450° F. (790° C.)
0.309	6.5	0.02	0.02
0.307	8.0	0.40 to 0.80	0.02
0.305	9.0	0.28 to 0.56	0.02
0.303	10.0	0.25 to 0.40	0.02; a few 0.18
0.302	11.0	0.20 to 0.25	0.20 to 0.25
0.300	12.5	0.15	0.15
0.297	16.0	0.07	0.07
0.286	20.0	0.05	0.05
0.277	25.0	0.02	0.02

Samples that received between about 8 and 10 per cent reduction of area and in which grain growth was produced by subsequent annealing at temperatures between 1290 and 1400° F.

[1] From the author's investigation, July, 1911.

(700 to 760° C.) were refined by simply heating to a temperature slightly above 1435° F. (780° C.). The samples that received a reduction of area more than about 10 per cent did not refine at 1435° F. (780° C.). For refining, heating to 1650° F. (900° C.) or higher was required. Apparently, 10 per cent reduction of area is a *critical* deformation. Refining at approximately 1435° F. (780° C.) is further evidence that this temperature is a critical point.

Prevention and Removal of Grain Growth in Drawn or Rolled Products.—Grain growth is caused by a *slight* deformation followed by annealing at temperatures between 1290 and 1435° F. (700 and 780° C.) or between 1290 and 1650° F. (700 and 900° C.). Grain growth can be prevented, therefore, by increasing the amount of deformation or by annealing outside the danger range or by a combination of both methods. If the deformation has been comparatively small, refining can usually be obtained by heating to temperatures above 1435° F. (780° C.); if somewhat greater, refining will require heating to 1650° F. (900° C.) or higher. If the annealing temperature is below 1290° F. (700° C.), little or no grain growth will follow deformation. For the prevention of grain growth, therefore, three general methods are used: increasing the amount of deformation until no grain growth can result; annealing at temperatures below 1290° F. (700° C.); annealing at temperatures above 1435° F. (780° C.) or above 1650° F. (900° C.) as required. Increasing the amount of reduction is a simple method of preventing grain growth in such products as wire and cold-rolled strip. In other processes, however, the amount of deformation is not so easily controlled. In hot rolling strip or sheet steel, grain growth is apparently dependent on finishing temperature as well as reduction, neither of which can be easily controlled. Reduction in cold-rolling sheet is not easily regulated because of variation in gage that is sometimes local. In cold-rolled sheet, grain growth often occurs in patches, probably because of local variations in thickness. This is shown on a small scale by Fig. 36. The amount of deformation in pressings depends on the shape to be produced and is, therefore, not readily controlled, although grain growth can sometimes be avoided by increasing the amount of deformation before annealing, a possibility with deep-drawn pressings.

When grain growth cannot be prevented by regulating the mechanical work, or deformation, control by heat treatment is

possible. For example, hot-rolled sheet can be refined by heating to temperatures above 1650° F. (900° C.) when refining is necessary. Grain growth in cold-rolled sheet may be prevented by a combination of treatments, the hot-rolled sheet being heated to 1650° F. (900° C.), if grain growth is present, before cold rolling. Cold rolling is then followed by annealing at temperatures below 1290° F. (700° C.), 1200 to 1250° (650 to 675° C.) being an average range. Similar treatment can be applied to cold-rolled strip. The treatment of pressings may be more complicated.

Grain Growth in Pressings. Prevention and Removal.—Cold pressing (or stamping) is a process by which steel rolled flat into plate, sheet, or strip is formed into various shapes, usually with a punch and die. Pressings, or stampings, are

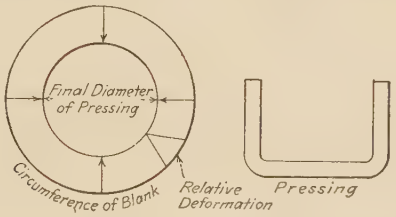


FIG. 38.—Illustrating deformation of pressing.

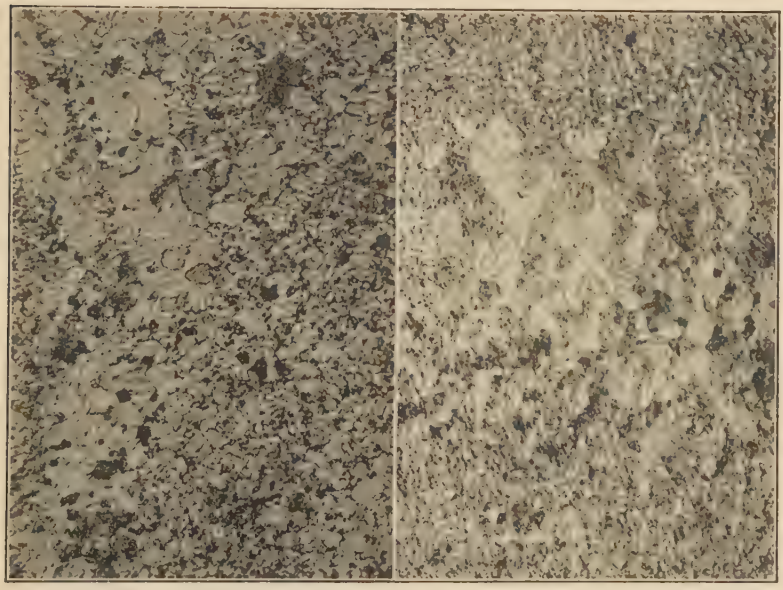
almost always formed without heating, and low-carbon steel is, therefore, used because of its ductility. Like wire drawing, pressing may require annealing between operations or after the finished shape has been produced because of the hardening effect of deformation. This combination of cold forming and annealing may easily, and frequently does, result in grain growth. Furthermore, some raw material, hot- and cold-rolled sheet and strip, may contain large grains when received, also because of grain growth. That grain growth should have been commonly accepted as a normal condition in stamping is not surprising.

How the mechanical work, or deformation, of cold pressing, followed by annealing, can introduce large crystals can be illustrated by one of the simpler forms produced by the process, a cup-shaped pressing (Fig. 38 (*a*)). This cup is formed by a cylindrical punch and die from a flat blank (Fig. 38 (*b*)). It is quite evident that the change of shape, deformation, has been greatest at the top, open end, of the cup and least at, or near, the

(*a*) (*b*)

FIG. 39.—Parallel strips from "cup" pressing as shown. (*a*) Held ½ hour at 1300° F. (705° C.), (*b*) held ½ hour at 1450° F. (790° C.).

bottom, with gradually decreasing deformation from top to bottom. This gradual variation has been indicated diagrammatically by the (V) on the blank. If such a pressing is heated to some temperature between 1290 and 1435° F. (700 and 780° C.), grain growth will result as shown in Fig. 39 (*a*), large grains at the bottom of the pressing with a decrease in size toward the top corresponding to the increase in deformation. Because of the space required, the photograph does not include all of the area of normal grain



(*c*) (*d*)

FIG. 39 (*Continued*).—Parallel strips from "cup" pressing as shown. (*c*) Strip *a* held ½ hour at 1300° F. (705° C.) reheated to 1450° F. (790° C.), (*d*) held ½ hour at 1250° F. (675° C.).

size extending to the top of the pressing but only the lower part, enough, however, to illustrate the reduction of the grain size to normal as deformation becomes greater.

Because of the increased deformation, grain growth may be prevented by deeper drawing in one or more operations before annealing, but if this is not feasible, grain growth can be prevented by annealing at the higher temperatures, 1450° F. (780° C.) or 1650° F. (900° C.), as required. Figure 39 (*b*), a photomicrograph of a strip parallel to the strip illustrated in (*a*), shows the result of annealing at 1450° F. (780° C.). Some grains of fairly large

size still remain, and complete refining would have required heating to a temperature above 1650° F. (900° C.), but such grains would rarely cause trouble. The removal of large grains by heating to 1435° F. (780° C.) is illustrated by the photomicrograph of Fig. 39 (*c*), showing the effect of heating strip *a* to that temperature. The grain growth produced by annealing at 1290° F. (700° C.) is almost entirely removed, the result being similar to that obtained with strip *b*, annealed at 1435° F. (780° C.). That annealing below the danger point is often better practice is illustrated by Fig. 39 (*d*), a photomicrograph of a strip parallel to *a* but annealed at 1250° F. (675° C.). Here grain growth is very slight. Quite often, no grain growth at all occurs on annealing at 1250° F. (675° C.), but no explanation of this variation has been given.

The selection of the proper annealing temperature evidently depends upon the requirements. Temperatures between 1200 and 1250° F. (650° and 675° C.) are usually high enough for softening and are, therefore, recommended for general practice, because no serious grain growth will occur. On the other hand, maximum ductility may be required for which a higher temperature will be necessary. For this ductility and to prevent grain growth, heating to 1450° F. (790° C.) is necessary and usually sufficiently high. The refining obtained at this temperature, however, for reasons already described, may be insufficient, and for complete refining heating to 1650° F. (900° C.) may be necessary. The proper temperature must be determined by experience or by trial, but annealing below the critical range is to be preferred when possible because of the lower cost and comparative freedom from scale. The higher temperatures will seldom be required if the sheet or strip used is free from grain growth.

Annealing for Ductility.—Ductility, as already indicated, determines the amount of deformation that is possible without breakage and is, also, some measure of resistance to shock. In other words ductility is an indication of the punishment that steel will stand when bent, pulled, drawn, or otherwise deformed. The conventional standard of ductility is the elongation and reduction of area determined by the tensile test. Increase in ductility is usually accompanied by a lowering of the elastic limit and tensile strength; and decrease in ductility, by an increase in the other properties. An increase in ductility resulting from grain refining, however, is usually accompanied by an increase

in the elastic limit and tensile strength. Annealing for grain refining is sometimes required to obtain ductility, and annealing for machinability is usually based upon increasing the ductility unless the carbon content is low. Such objects, however, are not always included in annealing for ductility, but may require heat treating to obtain the desirable combination of physical properties. The object of annealing to remove the effect of cold work is an increase in ductility, but hot-formed steel usually requires annealing for ductility to remove the hardening effect of cooling in air or else to refine the crystalline structure. Both may be the result of one operation. Refining requires heating to temperatures above the critical range, but if refining is not required, there are several methods by which ductility may be increased. The method selected will depend upon the steel, but three are generally employed. The steel to be annealed may be heated to temperatures just below the critical range and held or may be heated to temperatures just above the critical range and cooled in air or may be so heated and cooled slowly, as in a furnace. The last method is preferred for maximum ductility. The effect of annealing can be illustrated best by a comparison of physical properties, of which examples, taken from a series of tests, will be given. The results of hardening and drawing are included for comparison. These figures are presented for illustration, not as exact under all conditions.

COMPARATIVE PHYSICAL PROPERTIES OF HEAT-TREATED AND ANNEALED CARBON STEELS

Bars 1½ in. in diameter were treated as stated and machined to 0.505-in. diameter for tensile test.

1015 steel; 0.15 per cent carbon; quenched water from 1675° F. drawn as shown

Drawing temperature, degrees Fahrenheit	1,100	1,300	1,400
Elastic limit	47,000	42,000	43,000
Tensile strength	60,000	55,000	55,000
Elongation in 2 in., per cent	38	40	39
Reduction of area, per cent	74	76	70

Air anneal. Heated to temperature indicated and cooled in air

Temperature of heating, degrees Fahrenheit	1,200	1,400	1,650
Elastic limit	36,000	34,000	39,000
Tensile strength	52,000	53,000	53,000
Elongation in 2 in. (per cent)	39	39	39
Reduction of area (per cent)	65	70	70

COMPARATIVE PHYSICAL PROPERTIES OF HEAT-TREATED AND ANNEALED CARBON STEELS (*Continued*)

Furnace cooled to 1100° F. from temperature indicated

Degrees Fahrenheit	1,400	1,500	1,650
Elastic limit	34,000	34,000	44,500
Tensile strength	50,000	50,000	49,000
Elongation in 2 in., per cent	40	39	39
Reduction of area, per cent	70	69	66

PHYSICAL PROPERTIES OF COARSE-GRAINED BAR

Elastic limit	21,000
Tensile strength	35,000
Elongation in 2 in., per cent	27
Reduction of area, per cent	50

1050 steel; 0.51 per cent carbon; water quenched from 1540° F.; drawn as shown

Drawing temperature, degrees Fahrenheit	1,100	1,200	1,300	1,400
Elastic limit	86,000	74,000	66,500	53,000
Tensile strength	117,000	101,000	91,500	78,000
Elongation in 2 in., per cent	19	23	26	27
Reduction of area, per cent	46.5	55	58	48

	Air annealed from temperature			Furnace cooled from		
Degrees Fahrenheit	1,200	1,400	1,600	1,400	1,500	1,600
Elastic limit	46,500	55,000	54,000	54,000	55,000	57,000
Tensile strength	85,500	80,000	88,500	79,000	81,000	79,000
Elongation in 2 in., per cent	25	26	24	28	26	25
Reduction of area, per cent	40.5	42	39	45	42	38.5

1085 steel, 0.83 per cent carbon

	Water quenched from 1480° F. and drawn at			
Degrees Fahrenheit	1,100	1,300	1,400	1,480
Elastic limit	124,000	79,000	55,000	56,000
Tensile strength	154,000	104,000	84,000	105,000
Elongation in 2 in., per cent	15	23	25	19
Reduction of area, per cent	35.5	51	51	29

COMPARATIVE PHYSICAL PROPERTIES OF HEAT-TREATED AND ANNEALED CARBON STEELS (*Continued*)

Air annealed

From degrees Fahrenheit	1,200	1,300	1,425	1,475	1,550
Elastic limit	84,000	82,000	72,500	55,500	98,000
Tensile strength	121,000	115,000	109,000	104,000	133,000
Elongation in 2 in., per cent	12	14	19	21	10
Reduction of area, per cent	15	15	30.5	32	14

Furnace cooled to 1100° F.

From degrees Fahrenheit	1,250	1,350	1,400	1,475	1,525	1,600
Elastic limit	90,000	74,000	65,000	61,500	75,000	76,000
Tensile strength	116,500	106,000	87,000	88,000	105,000	106,000
Elongation in 2 in., per cent	14	18	28.5	22	15	5
Reduction of area, per cent	18	25.5	50	32	19	6

Heating Methods. Box and Open-fire Annealing.—Pieces of steel to be annealed may be heated in the furnace directly or in containers. Although direct heating is usually less costly, containers may be preferred in order to reduce the amount of scale formed or for ease in handling. Scale, however, need not be troublesome and can be controlled, although not easily if furnace temperatures are high and the time of cooling slow. Ordinarily, a small amount of hydrochloric (muriatic) acid, thrown into the furnace with the cold charge, will so loosen scale that it can be easily removed. The formation of heavy scale often follows the use of a reducing atmosphere in the furnace rather than oxidizing, apparently contrary to theory. Heavy scale is sometimes due to heating to temperatures above the desired point because of lack of equipment for correct temperature control. By better control and the use of methods such as those that have been indicated, annealing in the open fire can be carried on with little difficulty due to scale. On the other hand, box annealing may sometimes permit easier handling with less cost for labor, especially if a large number of comparatively small parts are to be treated. Unless box annealing is to be preferred for such a reason, heating should be carried on directly in the open furnace, a method that has, in many operations, replaced the more expensive box annealing once thought necessary.

CHAPTER VI

HARDENING PROCESSES

CYANIDING. NITRIDING. TOOL HARDENING

Description of Hardening.—The principles upon which the hardening of steel is based have been discussed in connection with quenching. Here attention will be given to the application of these principles to industrial practice. The hardening of steel has been described as *a process of heating to temperatures above or within the critical range followed by quenching for the purpose of markedly increasing the hardness of steel.* The hardness resulting from quenching can be modified by tempering.

The proper hardening of steel depends upon three factors, namely, composition (carbon and alloy content), proper heating, and proper cooling. To these may be added a fourth, proper tempering, or drawing. Tempering is not a part of the hardening process. It may be considered a softening process, but, because it is a method by which hardness is moderated, tempering will be included in hardening processes. In describing quenching, hardening has been explained as a *fixing* of solution structures. The hardness obtained by quenching depends upon the resulting structure, which, in turn, depends upon the carbon content (and alloy) and upon the rate of cooling. The rate of cooling depends upon the temperature of the steel at the time of quenching, the size of the piece, and the nature of the quenching medium. The conditions that control the hardness obtained by quenching, the "mechanics" of the process, to borrow a word, have been discussed. Here an attempt will be made to describe industrial methods, the "applied mechanics," so to speak.

Effect of Carbon on Hardening.—Industrial hardening depends, first of all, upon carbon content, because of the wide range of hardness obtained by varying the amount of carbon present. The same degree of relative hardness can be obtained with steels of different carbon content, if this difference is not too great, by changing the quenching medium or by changing the drawing temperature, allowing some but, nevertheless, a limited

freedom. For example, file hardness cannot be obtained by the simple heating and quenching of low-carbon steel, containing, for example, 0.10 per cent of carbon. The hardness obtained by hardening with one quenching medium gradually increases with increase in carbon, and the range of carbon content that will give the result desired at the lowest cost and by the simplest method will be selected. For close control, carbon is usually specified within a comparatively narrow range, usually within *ten points*, for example 0.30 to 0.40 per cent, but, in general, steel is classified in three grades, high carbon, medium carbon, and low carbon. Although there will be some overlapping, high-carbon steel may be presumed to contain from 0.60 to 1.50 per cent of carbon, medium-carbon from 0.30 to 0.60 per cent, and low carbon less than 0.30 per cent.

In general, high-carbon steel is used when a maximum hardness is desired—file hardness—and medium-carbon, when the hardness desired is moderate—to be obtained by drawing after quenching—although there are many exceptions to this. For example, high-carbon steel may be hardened and drawn for toughness, and medium-carbon steel, in thin sections, may be hardened to a high degree and not drawn. Medium-carbon steel, however, is usually employed when only a moderate degree of hardness is desired, for example in structural parts intended to resist shock without breaking and without bending. The use of high-carbon steel in such parts may be possible, but the use of medium-carbon steel permits a wider latitude in treatment, requires a lower drawing temperature, and is more easily handled.

Low-carbon steel can be hardened but slightly by ordinary treatment, although noticeably if the quenching is drastic. By case hardening, however, the surface can be made extremely hard, but the case is high-carbon steel. Low-carbon steel is case hardened if great surface hardness is desired, but a considerable increase in hardness can be obtained by very drastic quenching.

Effect of Alloying Elements on Hardening.—The range of hardening can be extended by the addition of alloying elements to steel. A greater degree of hardness can be obtained than with carbon steel, presuming the same carbon content; a desired degree of hardness can be obtained with a less drastic quenching medium, for example oil instead of water; and the depth of hardening will be increased, presuming that martensite and not austenite is the structure obtained.

The greater hardness that can be obtained with alloy steel is sometimes desirable for heavy duty, *i.e*, duty beyond the capacity of hardened carbon steel. Alloy steel may also be preferred even if satisfactory physical properties can be obtained with carbon steel because the hardness desired is more easily obtainable or because of the greater toughness for the same degree of hardness. Because a less drastic quenching medium may be used, oil can replace water without a sacrifice of the hardness desired. Distortion on hardening is sometimes due to too drastic quenching, and oil-hardening steel may, therefore, be preferred to water-hardening steel. Alloy steel hardens to a greater depth than carbon steel, a point already discussed. Below the surface of a piece of steel the rate of cooling becomes slower until martensite will be replaced by troostite and sorbite, as illustrated in Fig. 23. The fracture of a large piece of high-carbon steel is similar to the fracture of a case-hardened piece of steel. If alloying elements are present, martensite will be formed at a greater depth than in carbon steel with a corresponding hardening effect, presuming the other conditions to be practically alike.

Preliminary Treatment.—Because of the effect of carbon and of alloys on the results of the hardening process, steel of the right analysis must be obtained and the composition known. The condition of steel before hardening is of equal importance. Methods of determining composition and condition will be considered in connection with inspection. Preliminary treatment before hardening, normalizing and grain refining, is often required to obtain proper grain size on hardening. Such treatment may be necessary for parts to be machined before hardening so that distortion will be reduced, but normalizing can often be omitted by avoiding overheating in rolling or forging. Steel of high-carbon content may also require annealing for machinability.

Heating Methods. Preheating and Forcing.—The results of the second operation of hardening—quenching—have been described. Presuming close control of temperature and uniform heating, quenching is more important than the first operation—heating—but though quenching may control the results, the rate of production and the cost of industrial hardening will depend upon the methods of heating. The speed with which hardening can be carried on depends upon the furnace load and the rate of heating. Heating one small piece of steel in a large furnace is

not difficult but is not production. On the other hand, time may be lost if too much material is placed in a furnace because of the slow rate of heat transfer from one piece to another or because of the increased time required for heating as compared with the time required for a normal load.

To obtain uniform heating, a furnace load must be evenly distributed to take full advantage of the radiant heat of the furnace and the heat of the gases and to avoid heating by conduction through the material as far as possible, points discussed in another chapter. The proper load for a furnace can be determined by trial or from past experience. Such a load may be made up of pieces of the same size or of a number of pieces that vary in size, and for such different loads, different methods of heating may be necessary.

A cold charge may be heated gradually to the hardening temperature in a furnace that is not allowed to become hotter than the hardening temperature. This method, however accurate it may be, is not satisfactory for the heating of a number of parts that differ considerably in size—for example, tools. Small tools will soon reach the hardening point, but larger tools will require longer time, thus slowing down production. To increase the output, without sacrificing accuracy of temperature control, a separate preheating furnace may be employed. Parts to be hardened will be preheated to a temperature near the hardening point and then transferred to the hardening furnace, which is maintained at the hardening temperature. Cooling of the hardening furnace by introducing a cold charge is avoided by preheating. Final heating requires comparatively little time, and the operator, beyond occasional observance and regulation of the temperature of the furnaces, is free for duties other than watching the progress of heating. Preheating is often employed in production hardening when molten baths of lead or salts are used, particularly if the bath is small. Preheating not only saves time in the bath, but also prevents the formation of a solid layer of lead or of salts on the piece, which will occur if the steel is cold.

Preheating, however, is not the best method for increasing production from a furnace if large numbers of similar parts are to be handled. More rapid production can be obtained by raising the temperature of the furnace well above the hardening point to increase the rate of heat transfer. A cold charge will lower

the temperature of an *in-and-out* furnace, but, on heating, the temperature of the furnace will reach the hardening point long before the charge. Increase of the temperature of the furnace will decrease the time required to heat the charge. When the temperature of the charge approaches the hardening point, the supply of fuel is reduced or cut off, and the furnace allowed to cool to the hardening temperature. This method requires some care in determining the proper operating conditions, but when these have once been determined, a routine can be established.

In continuous furnace practice, the temperature of the furnace is usually well above the hardening temperature, passage through the furnace being so regulated that the pieces being heated will reach the proper hardening temperature at the outgoing end of the furnace. Determination of the most suitable furnace temperature and of the time required to pass through the furnace requires only a few simple tests. The furnace must be properly designed, however, and correctly fired so that the distribution of heat will be the same at all times.

Time Required for Heating.—The time required for hardening is that necessary for uniform heating to temperature. Large pieces will require more time than small pieces and will, therefore, be held for a longer time if heating throughout is necessary. Holding in the furnace for a comparatively long time in order to heat throughout is called "soaking." When soaking is required, the temperature of the furnace is not much above the hardening point. If it is too high, overheating at the surface and deoxidation may result. The time required for soaking is best learned by experience, although rules have been offered. Differences in the rate of heating, however, make such rules untrustworthy guides. Long soaking will not be required if hardening of the surface only is required. A large load of small parts will require time to reach the hardening temperature, and the time required may be determined by observation. Time is of importance but not so much so that parts should be held at temperature longer than necessary. Rules for timing according to size and weight cannot be applied to all production. Heating through is sometimes unnecessary; for example, cutting tools that require hardening of the cutting edge only or dies to be hardened on one face do not require soaking, nor do thin pieces that heat through quickly.

Quenching and Quenching Equipment.—The second operation of hardening—quenching—usually requires more attention than heating, and, as suggested, herein lies most of the hardener's art. Although equipment has largely replaced personal skill in production hardening, the trained operator is still in demand, particularly in tool hardening. Even here, however, modern equipment has supplemented skill. In quenching, the hardener may be able, from experience, to obtain results in a still bath, particularly if the part is thin, but usually he will find it necessary to have a constant change of the quenching medium in contact with the steel to prevent too slow cooling. Until rather recently, this change of medium was usually provided by the good right arm of the operator, who would move the part rapidly to and fro in the bath, a method that is still common. No large number of parts, however, can be quenched in a comparatively short time without overheating the quenching medium, unless it is constantly changed and cooled. For a large production, therefore, a constant flow of the medium is now generally provided. For drastic quenching (this applies to both water and oil) the flow will be very rapid, and sprays and nozzles may be necessary to increase the pressure and to direct the flow. Even if drastic quenching is not called for, such equipment may be required to force the quenching medium into holes and corners. Mechanical agitators, and sometimes compressed air, are often used to keep the bath in constant motion. Such equipment is of value when parts are quenched all over, but it may be of even greater value for local hardening, by which is meant the hardening of only one portion of a piece of steel.

Local Hardening.—There are two ways of hardening locally, by local heating and by local quenching, although the two may be combined by both heating and quenching locally. For example, the cutting edge of a chisel may be hardened by heating only the edge and quenching or by heating all over and quenching only the edge. Which method to choose will depend upon the piece and upon the requirements. Sometimes either can be used, as just illustrated, but in this example local quenching would probably be preferred because the residual heat permits drawing. End hardening presents no particular difficulties, but all local hardening is by no means so simple. The combination of hardness and toughness that can be obtained by local hardening is so serviceable that demands are often made that cannot be

met in any other way and often in no simple way. For example, the local hardening of the edge of a disc presents a problem not solved by simple means.

This and other demands for similar local hardening can be met by the use of fixtures many of which are ingenious. Discs have been hardened at the edge only and in quantity by placing a number on a shaft and rotating them in a molten bath so that only the edge is heated. Automobile camshafts can be hardened on the cams and bearings only by the use of a fixture that prevents the quenching of the shaft between the cams and bearings. Small parts—gears, milling cutters, and circular saws, for example—can be heated or quenched with tongs or fixtures that will keep the center but not the periphery from reaching the hardening temperature or that will prevent contact between the quenching medium and the portion to be left soft. Figure 40 illustrates simple tongs for such local hardening. This

Fig. 40.—Quenching tongs.

principle is also applied to local heating in continuous furnaces, for example in the heating of mower and reaper blades to be hardened only at the edge. The conveyor is provided with fixtures that so hold the part that only the edge will be heated. A furnace so equipped is shown in Fig. 111.

Hardening from Temperatures within the Critical Range.—The temperature required for hardening has been described as above or within the critical range. Practically all industrial hardening depends upon heating to temperatures above the critical range for complete solution (excepting hypereutectoid steels). The formation of a solid solution on heating is a gradual process, however, beginning when the temperature of the steel reaches the critical range and continuing until the Ac_3 point is reached and solution is then complete. Quenching from within the critical range will therefore harden to some extent, this depending upon the amount of solution that is formed. But the structure will be troostitic rather than martensitic, at least in the pearlitic steels, and the hardness will, therefore, be insufficient for most

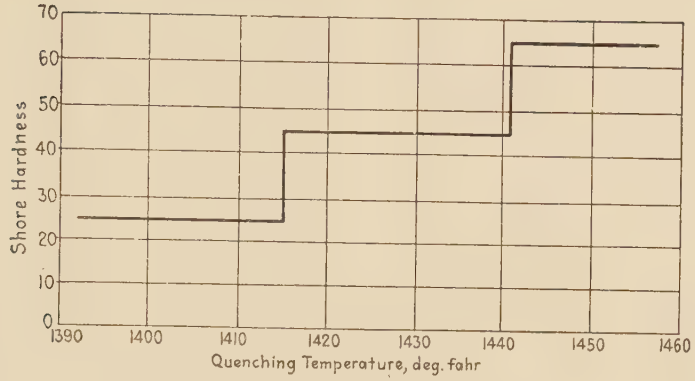


FIG. 41.—Shore hardness curve for S. A. E. 2315 steel (3½ per cent nickel) quenched as shown.

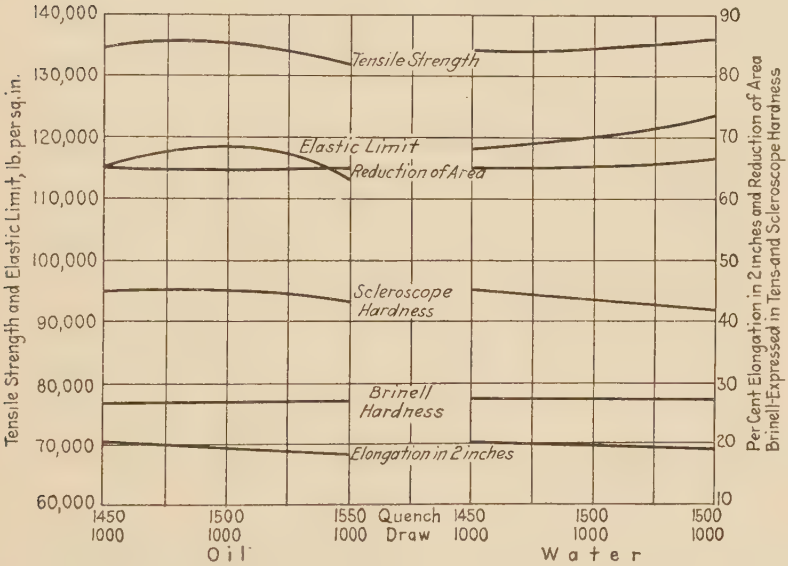


FIG. 42.—(*a*) Physical property chart for rise in quenching temperature.

ANALYSIS

Carbon	0.25–0.35
Manganese	0.50–0.75
Sulphur	0.045
Phosphorous	0.035
Silicon	0.10–0.20
Chromium	0.40–0.60
Nickel	1.25–1.75

Quenched and drawn as shown.
Bar diameter ⅞ in. round, annealed and machined to 0.520 in..

industrial purposes. Furthermore, thin pieces, quenched from within the critical range, will distort, sometimes badly. Such results account for one of the principal rules of early practice: *Do not harden on a falling heat.* Modern practice frequently

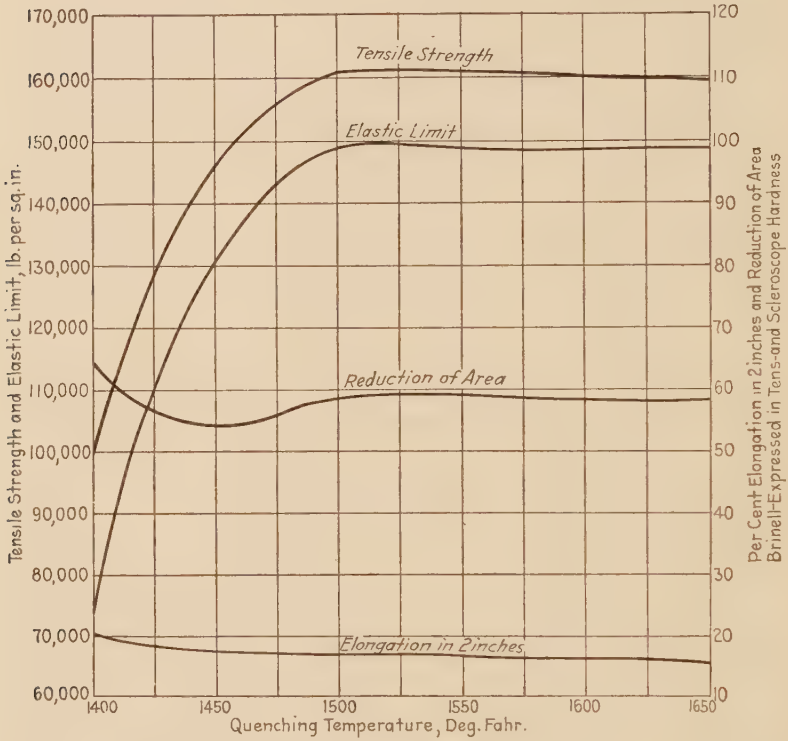


FIG. 42 (*Continued*).—(*b*) Physical property curves for rise in quenching temperature.

ANALYSIS

Carbon	0.23–0.28
Manganese	0.65–0.75
Phosphorus	0.035 max.
Sulphur	0.045 max.
Chromium	0.70–0.90
Molybdenum	0.25–0.35

Water quenched as shown and drawn to 1000° F.
Bar diameter 0.525 in. round.

breaks this rule but only under accurate temperature control by which quenching from within the critical range can be avoided.

The lower degree of hardness that results from quenching from temperatures within the critical range is sometimes desirable,

however, particularly for hardening carburized alloy steel. If the temperature of hardening is only a little above the upper critical point of the case, the core will not be hardened, this requiring a higher temperature because of the lower carbon. In practice, however, increasing the hardness of the core is often

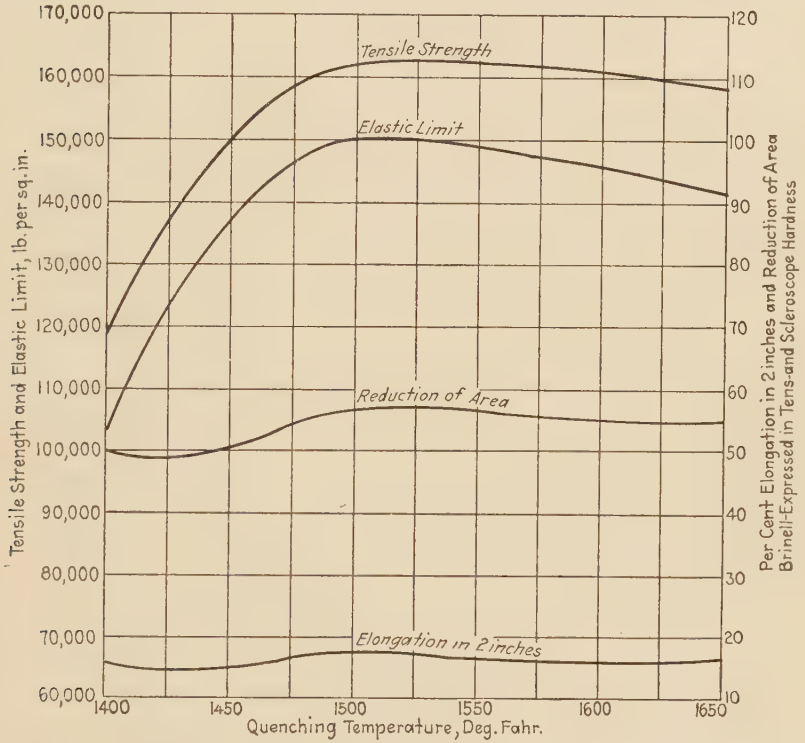


FIG. 42 (*Continued*).—(*c*) Physical property curves for rise in quenching temperature.

ANALYSIS

Same as 42(*b*)

Water quenched as shown and drawn to 1000° F.
Bar diameter ⅞ in. round.

desirable, and higher temperatures are, therefore, employed. The core will be completely hardened if quenched from above its critical range. The hardness thus obtained, however, is sometimes too great for the service required. A lower degree of hardness results if the quenching temperature lies within the critical range. This is illustrated in Fig. 41. More represen-

tative curves showing the effect of quenching from temperatures within and above the critical range are shown in Fig. 42.

The curve of Fig. 41 shows approximately the change in hardness on passing through and going above the critical range with a steel containing 3.5 per cent nickel and 0.15 per cent of carbon.

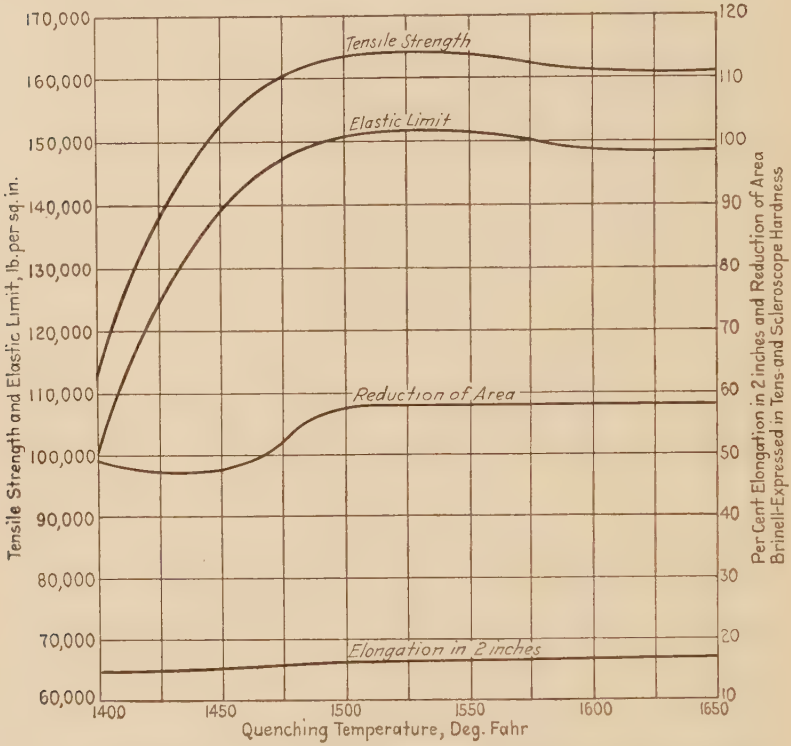


FIG. 42 (*Continued*).—(*d*) Physical property curves for rise in quenching temperature.

ANALYSIS

Same as 42(*b*)

Water quenched as shown and drawn at 1000° F.
Bar diameter 1¼ in. round.

More elaborate determination of physical properties is shown in the curves of Fig. 42. Such curves frequently neglect the effect of quenching at temperatures within the critical range, because this is of little importance in industry, but this effect is illustrated by Fig. 42. More complete curves are shown in Fig. 42 (*b*), (*c*), (*d*), and (*e*), of the same steel but with increasing size

of the test piece thus illustrating the effect of mass. The Ac_1 point of this steel starts at 1370° F., (745° C.) and the Ac_3 point ends at 1510° F., (820° C.) approximately. The effect of size on the physical properties should be noted. The increasing tensile strength (hardness) on passing through the critical range is accompanied by a drop in ductility, elongation, and reduction.

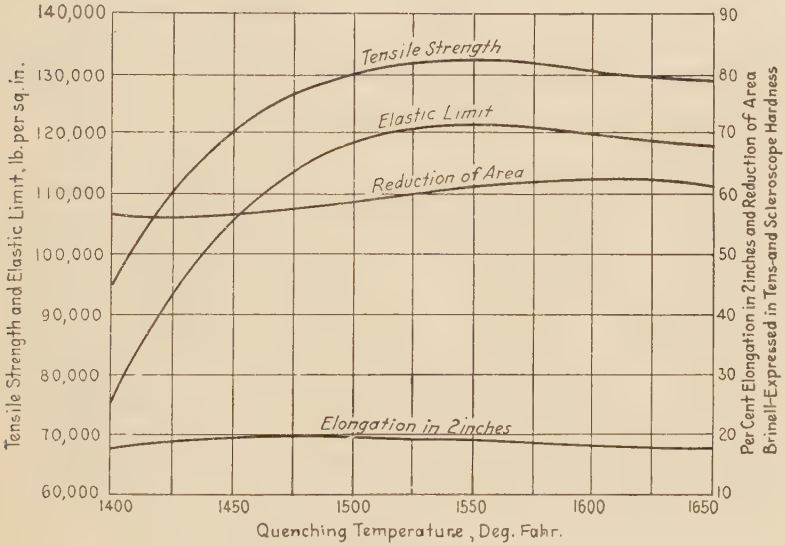


FIG. 42 (*Continued*).—(*e*) Physical property curves for rise in quenching temperature.

ANALYSIS

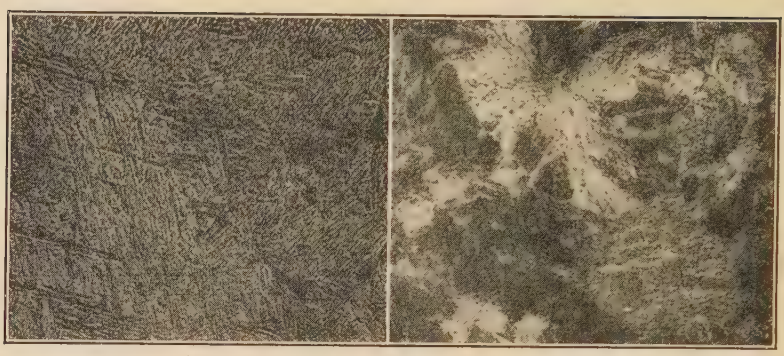
Same as 42(*b*)

Water quenched as shown and drawn at 1000° F.
Bar diameter 2 in. round.

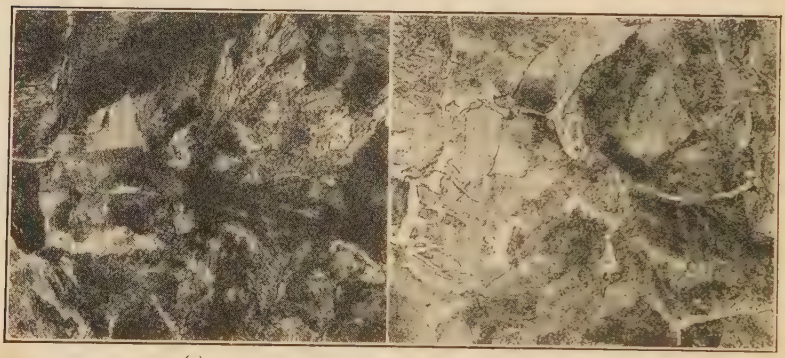
Determing the Proper Hardening Temperature.—These curves show the comparatively wide range of temperature permissible for quenching, illustrating the fact that hardening temperatures are not necessarily held within a few degrees, as popular opinion sometimes believes. The permissible range, however, varies with different steels. The hardening range of the chrome molybdenum steel illustrated is 1525 to 1550° F. (830° to 845° C.)

TEMPERING (OR DRAWING)

Object of Tempering.—Hardening is followed by tempering if a modification of hardness is desired, unless the result desired



(*a*) (*b*)



(*c*) (*d*)

(*e*)

FIG. 43.— 1055 steel, water quenched from 1550° F. Drawn as shown. 500 diameters. (*a*) As quenched Brinell hardness 627, (*b*) drawn 500° F. (260° C.) Brinell hardness 418, (*c*) drawn 750° F. (400° C.) Brinell hardness 340, (*d*) drawn 1000° F. (540° C.) Brinell hardness 302, (*e*) drawn 1100° F. (595° C.) Brinell hardness 255.

is obtained by using a selected quenching medium. As already described, tempering is a softening operation that gradually alters the quenching structure from martensite to sorbite, for example as illustrated in Fig. 43. Tempering can be distinguished from annealing, which may also be a softening operation, in that the aim is not maximum ductility but rather some combination of hardness and ductility, as illustrated in the charts and tables of physical properties. Drawing temperatures lie below the critical range; annealing temperatures may go above. If reheating to temperatures above the critical range followed by air cooling is required to obtain the properties desired, annealing, not hardening and drawing, will be the process selected. Tempering, however, may be carried on for the purpose of relieving strains set up by hardening rather than for obtaining a specific combination of physical properties. Reheating to 300 to 400° F. (150 to 200° C.) is advisable for tools and other parts that have sharp corners or that have an irregular shape. Some operators call such treatment "tempering," and reheating to higher temperatures for the purpose of obtaining desired physical properties "drawing," but this is not common practice.

Rate of Cooling on Tempering. Temper Brittleness.— Drawing temperatures being below the critical range, the rate of cooling will ordinarily have no effect upon the result. Air cooling is generally employed, but cooling in water or oil to save time is common practice. The rate of cooling, however, may have a marked effect upon the properties of the higher chrome-nickel steels, of which 3435 or 3445 are representative. Steels of this type sometimes become more or less brittle if cooled in air from the drawing temperature, a phenomenon know as "temper brittleness." The conditions under which temper brittleness occurs vary with different lots of steel, and not all steels of this type are subject to it. What these variable conditions are is not yet completely known, but the effect of temperature and cooling on drawing has been carefully investigated. Drawing at temperatures between 840 and 1150° F. (450 and 625° C.) followed by air cooling produces temper brittleness in some chrome-nickel steel. The actual range of temperature varies with different lots. Brittleness often results from heating to temperatures close to 975° F. (525° C.) regardless of the rate of subsequent cooling. Rapid cooling in oil or water from temperatures above 1100° F. (600° C.) prevents brittleness. To

remove temper brittleness requires heating to temperatures between 1100 and 1300° F. (600 to 700° C.). The addition of a small amount of molybdenum seems to prevent temper brittleness regardless of the method of drawing. The brittleness is shown more by the effect of shock or impact than by the tensile properties.

Baths for Tempering.—Drawing, or tempering, may be carried on in a bath furnace or on the hot plate (appliances that will be described later) or in the air furnace. The liquid bath is sometimes preferred because of rapid heating and presumably greater uniformity of temperature in comparison with the air furnace. The entire range of drawing temperatures is covered by liquid baths, but different compositions are required for different ranges of temperature. The oil bath is commonly used for drawing temperatures up to 550° F. (290 ° C.), oil for drawing. having a flash point of 600° F. (315° C.) at least. Molten lead is sometimes used to cover the range between about 950 and 1300° F. (510 and 705° C.). Common salt baths for drawing are

Potassium nitrate, per cent	40	55
Sodium nitrate, per cent	60	..
Sodium nitrate, percent	..	45
Melting point, degrees Fahrenheit	425 (218° C.)	280 to 300 (140 to 150° C.)
Range, degrees Fahrenheit	550 to 1000 (290 to 540° C.)	350 to 600 (175 to 315° C.)

The liquid bath has advantages in speed and in closeness of control, but the air furnace, heated by gas, electricity, or oil, is more favored because it will cover the entire range of drawing temperatures and is less costly to operate and maintain. Drawing furnaces may be heated directly by gas or oil if drawing temperatures are comparatively high. Indirect heating is sometimes preferred for drawing at comparatively low temperature by means of hot air supplied from a separate furnace. This method is very satisfactory, particularly if the temperature is controlled automatically. The electric furnace is extensively used for tempering because of the ease of control and for cleanliness.

CYANIDING

Cyaniding. Shimer Process.—Cyaniding is properly a carburizing process for shallow case hardening by means of a molten

bath containing sodium cyanide, which has now replaced the more expensive potassium cyanide. Ferro and ferricyanides can also be used but are more costly. Cyaniding replaces carburizing when only surface hardness—skin hardness—is desired. The time required is short, and the case from 0.002 to 0.005 in. deep as an average. Cyaniding is not entirely a carburizing process, as the hardness obtained may be due to the formation of hard nitride of iron. Cyaniding may be carried on at a temperature as low as 1400° F. (760° C.) and at temperatures within the hardening range, thus permitting hardening by quenching directly from the bath. The speed of penetration, however, is increased with rise in temperature. A molten bath is not always necessary, as powdered cyanide can be sprinkled on the hot steel.

At one time, cyanide was used alone, but, because less volatile and less costly, other salts are usually added. Representative examples of such mixtures are:

	Per cent	Per cent
Sodium cyanide (98 per cent)	25	30
Soda ash	25	25
Salt	50	45

Cyanide salts are volatile at high temperature, more so than the other salts used in these baths. Maintaining the correct composition will, therefore, require the addition of more cyanide than of the other salts. In practice, however, the standard mixture is used for replacement but is supplemented by occasional additions of cyanide.

Cyanide baths are also used for heating rather than for case hardening. The cyanide bath is used mostly, however, for the surface hardening of small parts of low-carbon steel. Nuts, bolts, washers, and other parts for which low-carbon steel is commonly used can be surface hardened to a degree sufficient for the service required. Such parts are not usually ground. Pins and other parts that require grinding to size are cyanided after grinding.

In the Shimer process for case hardening, the active agent is calcium cyanamide. The bath consists of calcium chloride and sodium chloride (salt). After placing the steel to be treated in the bath, calcium cyanamide is added, and immediately a gas, probably cyanogen, is liberated. This gas is the active agent

in the formation of carbide and nitride of iron by some reaction with the steel. To obtain the best results, a large quantity of gas should be liberated.

NITRIDING

Nitriding Process and Steel for Nitriding.—The Shimer process is, perhaps, part way between cyaniding and nitriding. Nitride of iron is extremely hard in itself and is frequently, if not always, present in steel that has been cyanided. A recently developed process, termed "nitriding," case hardens steel by forming nitride of iron. The active agent is ammonia gas. The parts to be nitrided are placed in retorts with the ammonia and raised to a temperature between 875 and 925° F. (630 to 655° C.). The time required is stated to be from 2 to 90 hours, the penetration after 90 hours being about $\frac{1}{32}$ in. According to the results of investigations, the time can be halved by increasing the pressure in the retort.

Ordinary commercial steels, including carbon steel, can be nitrided to obtain at least a skin hardness, but better results are obtained with steels containing alloys that form nitrides easily, for example chromium, molybdenum, aluminum in particular, and others. Various analyses are proposed, a typical steel containing 1.00 to 1.25 per cent of aluminum and about 1.50 per cent of chromium. About 0.20 per cent of molybdenum may also be present. Carbon may be as desired, for example 0.10, 0.30, or 0.45 per cent. Heat treating may be carried on after nitriding.

Nitriding has an advantage over carburizing in the low temperature required and, therefore, in avoiding distortion due to heating. A disadvantage is the brittleness of the case, particularly at sharp edges, but most of the difficulty can be avoided by rounding edges. The greatest disadvantage at present is the greater cost of special steels for nitriding, but it is possible that this may be removed. Other disadvantages lie in handling and in the time required, disadvantages that will probably be removed after practice has been continued. Nitriding is still in the stage of research and, therefore, too new for extended discussion but from the progress made will probably take its place beside carburizing.

TOOL HARDENING

Tool Hardening and Tool Steel.—The principles that have been discussed are just as applicable to the hardening of tools

as to the hardening of structural parts, and large numbers of tools of the same type may be handled in much the same way. But the tools that reach the hardening room of the average manufacturing plant differ so in size, shape, and in the service required that the methods of handling will ordinarily differ from those applied to structural parts. More care will be required, perhaps because of the design of the tool, perhaps because of cost. Tool hardening may, therefore, be an art in itself.

The steel required for tools is usually high in carbon, but high-carbon steel is not necessarily tool steel. Tool steel is usually distinguished by more rigid specification of composition and by greater care in manufacture. The so-called impurities, sulphur and phosphorus, are kept below the amount permitted in standard commercial steel, although there is some difference of opinion with regard to the necessity. Manganese in carbon steel is usually below 0.30 per cent as compared with 0.50 per cent or more in standard steel. The lower manganese is required to avoid *water cracking*. Manganese is an alloying element that increases the hardness obtained by quenching, so that if too much is present, water quenching may be too drastic. The content of manganese may be increased to 1.25 to 1.50 per cent or more to make an alloy steel that can be oil hardened. Such steel is termed "non-shrinkable" because it can be hardened in oil with little distortion, usually with much less distortion than that of carbon-steel water hardened.

Grades of Carbon Tool Steel and Their Applications.—For the whole range of tools, from pickaxes to dies, carbon steel is employed much more than alloy steel, and, as in production hardening, methods and results depend primarily upon the carbon content. The service required of tools varies so much that a wide range of carbon is required. A tool hardener can make a variety of tools with one grade of steel, but his work is made much easier and often less costly by supplying him with several grades of carbon steel and, also, alloy steels for special purposes. The range of carbon for tool steel lies between about 0.60 and 1.50 per cent, and this range is divided into grades by ranges of ten points of carbon. These grades are sometimes called "tempers" and may be distinguished by letters or numbers rather than by the carbon content. The usual commercial ranges and some examples of tools which each range is commonly used are as follows:

Carbon 0.60 to 0.70 per cent for tools requiring toughness: setscrews, drop-hammer dies, bolt sets, brick chisels, auger bits.

Carbon 0.70 to 0.80 per cent for hammers, drop-hammer dies, wrenches, chisels, mining drills, punches, rivet sets, shear knives.

Carbon 0.80 to 0.90 per cent for hot chisels, hand chisels, blanking and cold-heading dies.

Carbon 0.90 to 1.00 per cent for drawing dies, forming dies, cones, hammers, magnets, springs.

Carbon 1.00 to 1.10 per cent for lathe centers, milling cutters, drills, axes, drawing dies, lathe tools, jewelers' dies, punches, cones, trimming dies.

Carbon 1.10 to 1.20 per cent for drawing dies, thread-rolling dies (cold), punches for drawing, lathe tools, milling cutters, tools for working brass and bronze.

Carbon 1.20 to 1.30 per cent for files, wire-drawing dies, woodworking tools, glass cutters, tools for working brass and bronze.

Carbon 1.30 to 1.40 and 1.40 to 1.50 per cent for all tools requiring extreme hardness, tools for cutting hard metal, wire-drawing dies.

More complete lists of grades and uses can be found in catalogues furnished by makers of tool steel. Such lists are not intended to fix closely the carbon content that should be used for a particular tool but represent a general opinion about the grades best adapted for the different purposes, taking into consideration the equipment that is usually at the hardener's disposal. If one grade is not at hand, the next grade below or above will give equally good results, provided the hardener knows that the change has been made, so that he can change his hardening and drawing temperatures accordingly.

Alloy Tool Steels.—All types of alloy steels can be applied to tools. Alloy tool steels usually differ from the standard commercial alloy steels very slightly and often only in that small amounts of vanadium, molybdenum, or chromium have been added if not already present. These additions may widen the range of temperature of hardening. The pearlitic manganese steels containing between 1.00 and 1.80 per cent of manganese and about 0.90 per cent of carbon are converted into tool steel by the addition of small amounts of other elements. The so-called "non-shrinking" steels are of this type.

Steels of the 3100 series, low chrome nickel, particularly 3140 or 3145, find service in forging dies and other tools but are altered by the addition of other elements. For forging and other dies, a Brinell hardness of 450 to 475 is desirable.

A more expensive die steel but more suitable for heavy duty contains 2.00 to 2.5 per cent of carbon and from 10 to 15 per cent

of chromium, averaging about 12 per cent. The carbon content is sometimes lowered to 1.00 per cent, but the higher carbon is preferred. This steel is air hardening and is, therefore, usually quenched in an air blast, although oil is the better quenching medium. If hardened from about 1775° F. (970° C.), the structure will be martensitic, Rockwell hardness about 65, but if the hardening temperature ranges from 1900 to 1950° F. (1040 to 1065° C.), the structure will be austenitic and the Rockwell hardness about 50.

A chromium steel containing about 3.50 to 4.00 per cent chromium and 0.80 to 0.90 per cent of carbon is used for hot-forming dies and is also air hardening but usually quenched in oil. The hardening temperature is about 100° F. (55° C.) higher for air hardening than for oil, and the hardening range lies between 1700 and 1800° F. (925 and 980° C.). The Brinell hardness resulting is over 600; Rockwell hardness, about 65. For dies, this steel is drawn for Brinell hardness 400 to 450; Rockwell hardness 45 to 50.

Tungsten is a valuable element in steels for hot-forming dies. High-speed steel is often used for this purpose, but less expensive steels are available. One contains from 3.00 to 5.00 per cent of tungsten and about 1.40 carbon. Small amounts of chromium and vanadium may also be present. The hardening temperature is somewhat below that of high-speed steel, being between 1900 and 2100° F. (1040 and 1150° C.). With a water quench, a Rockwell hardness of 65 is obtained. Tungsten in smaller amount is used in a steel for taps and dies. The percentage of tungsten is about 1.50 to 2.0 per cent, and carbon 1.15 to 1.25 per cent. Small amounts of chromium and vanadium may be added.

Other examples can be given, but these are typical. The advantages of alloy steel over carbon steels have been mentioned. In tool hardening, the less drastic quenching and the far greater depth of hardening are the most important. Alloy steel is not always better than carbon steel; carbon steel will sometimes give better service, but for some purposes, for example blanking, heading, and forging dies, alloy steel is preferred because of the longer life of the tool.

Preliminary Treatment of Tool Steel.—Tool steel, particularly carbon steel, is usually normalized, refined, and annealed before being placed on the market if intended for valuable tools. Such

a complete treatment may not always be necessary but will be good insurance, particularly if the cost of machining excedes the cost of the steel for a tool. By such treatment ordinary commercial high-carbon steel can often be made suitable for tools. Common treatments for carbon steel are

Normalize..... { Heat to 1550 to 1600° F. (845 to 870° C.)
Cool in air (or quench in oil)

Refine.....Heat to 1420° F. (770° C.)

Anneal.....Cool slowly in furnace to 900° F. (480° C.) or

Normalize..... { Heat to 1550 to 1600° F. (845 to 870° C.)
Cool in air (or quench in oil)

Refine..... { Reheat to 1420° F. (770° C.)
Quench in oil

Anneal..... { Reheat to 1250 to 1275° F. (675 to 690° C.)
Hold for time required
Cool in furnace or in air to 900° F. (480° C.)

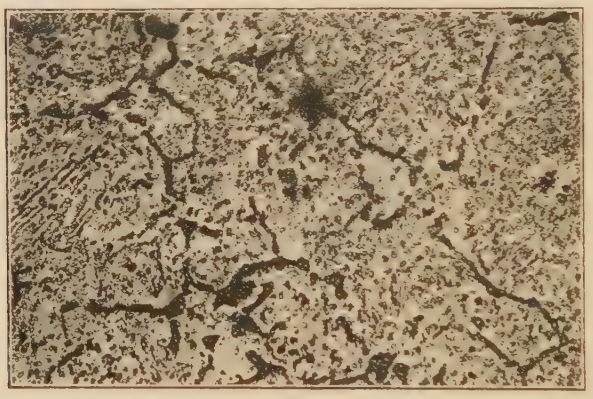


Fig. 44.—1.25 per cent carbon steel spheroidized. 500 diameters.

Similar treatment can be applied to low-alloy steel. Furnace cooling can be replaced by cooling in a bed of lime or mica, a method once common. The object of annealing—spheroidizing—has been discussed, and the structure illustrated in Fig. 30 Another illustration of a steel higher in carbon is shown in Fig. 44, a spheroidized steel containing 1.25 per cent of carbon. The cementite is black because the sample was etched in sodium picrate.

Tools require more care in heating than structural parts. The high-carbon content calls for close control of temperature and uniform heating to avoid distortion and, also, breakage if the

tool is of large size or irregular section. The temperatures required can be determined from the working diagrams, but thin tools are heated to a temperature not far above the critical range. From the pearlite point and beyond, increase in carbon does not change the critical range, but the higher carbon steels are heated to temperatures at the bottom of the working range.

Equipment for Heating Special Tools.—Some tools are best heated in special furnaces, for example a broach, a tool that is usually long and with deep and often sharp depressions at intervals. Such tools will distort but little if heated in a vertical position, and for them vertical hardening furnaces should be provided. Special equipment will soon pay for itself if many tools that require such equipment are treated. The loss of a few expensive tools will more than balance the cost of such equipment.

Tricks in Heating.—In tool hardening, the operator has many opportunities to demonstrate skill, particularly if equipment for

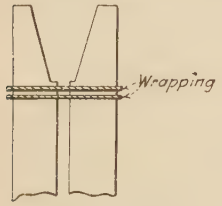
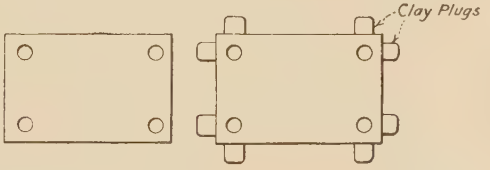


Fig. 45.



(*a*) (*b*)

Fig. 46.

special tools is lacking. No skilled hardener is at a loss, for example, in hardening a broach without a vertical furnace if he can have a piece of pipe just large enough to hold the tool. Heated in the pipe, distortion will be small. Many problems due to design confront the hardener. Some are unnecessary and due to neglect on the part of the designer, but others cannot be avoided—for example, the required design shown in Fig. 45. The concave section must be hard, but the walls are so thin that cracking may occur on hardening. To avoid this, the skilled hardener wraps wires around the tool and covers them with a mixture of clay and asbestos, as is illustrated in Fig. 45. Figure 46 (*a*) represents a common problem. The corners tend to spall off in hardening and will do so readily if holes are present. The ordinary hardener will try to avoid cracking by filling the hole with clay, but the skilled hardener will make sure by adding

lumps of clay, as shown in Fig. 46 (*b*), or may, perhaps, cover the corners completely so that they will not be hardened.

Quenching Methods and Equipment.—In quenching rather than in heating will be found most of the tricks of tool hardening. The apprentice soon learns to move a tool rapidly in a still quenching bath or to agitate the bath if the tool is too large for such handling. Tool hardeners develop many peculiar methods of quenching. For example, one operator stirs the bath violently, then drops in a small slice of potato below which he quenches the tool. Such methods may amuse the scientifically trained, but frequently a good reason for them exists. Here the potato has nothing to do with the treatment but rests in the vortex of the small whirlpool that the stirring has formed and indicates the center of motion. Such tricks become unnecessary if the bath is in constant and rapid circulation.

Part of the tool hardener's art lies in local hardening. Many tools of which blanking, trimming, beading, and cold-heading dies, shear knives, and drop-hammer dies are examples will usually require hardening on one face only. Such tools may be quite long or quite large and may warp or crack if hardened all over. A skilled hardener, therefore, avoids trouble by hardening only the working face or edge, immersing the tool in the bath just deep enough for the purpose and with motion if possible. Large tools, however, are not easily kept in motion when partly immersed in a bath, and soft spots may easily occur even in a circulating bath. Provision should be made for a strong flow of the quenching medium at the top of the bath. Even a common garden hose can be used, but permanent equipment, perforated pipe at the top of the bath, will give better results. The tool hardener is more concerned with avoiding warpage and breakage than with soft spots. Having a choice of two evils, the one from which complaints will quickly develop—breakage—will be rejected in favor of the other from which no complaint may arise. Without ample flow at the surface, soft spots will usually occur because of the heated layer of liquid at the surface and because of vapor pockets.

Some tools, of which a drawing die is an example, require hardening on internal or recessed faces where vapor pockets are easily formed unless a strong flow of the quenching medium is provided. To obtain sufficient flow in holes often requires the use of special nozzles or sprays. Figure 47 shows a convenient

permanent fixture for internal quenching, one that can be built into any quenching tank. The fixture, which can be fitted to the main inlet, for which a separate inlet may be provided, consists of a pipe fitted at the bottom end with a flange through which two holes are drilled. The flange of the inlet pipe is provided with studs so arranged that the fixture can be placed over the inlet pipe and held in place by the studs. A bayonet lock permits quick placing and removal. The outlet hole at the top of the fixture can be reduced, if desired, by similar fittings and smaller pipe. In the sketch is also shown an added perforated pipe by which additional flow at the surface can be obtained.

The work of the operator can be made much easier in either complete or local quenching by providing fixtures to hold tools in place while quenching, fixtures that need not be elaborate. A grating or simple cross-bars will often be all that is necessary. Such fixtures can save much time for the operator, releasing him for other work while the tools are cooling in the tank. When such fixtures are used for local quenching at the top of the bath, provision for a flow of the quenching medium at the surface should always be made. Nozzles for internal quenching, for example in hardening drawing dies, and fixtures for guiding the flow are also convenient.

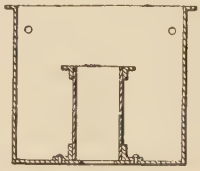


FIG. 47.—Fixture for internal quenching.

Tempering Tools.—Tools may be put into service after hardening, but, for reasons already explained, tempering is generally required. The air furnace or bath can be used if the entire piece is to be heated. On the other hand, such equipment cannot always be used if different degrees of hardness are required in the same piece. The opposite ends of a bar can be drawn in the air or bath furnace at different temperatures, but a gradation of hardness throughout calls for different equipment. For this purpose, the hot plate is usually employed. This may be a piece of boiler plate heated in a furnace or the flat top of a stove designed for the purpose. The end or face of the tool that is to be the softest is placed against the hot plate. Heat travels so slowly through a tool that an even gradation of hardness can be obtained. In much the same way can a gradation of hardness be obtained in a bar heated all over and quenched at one end by drawing with the residual heat. For example, a chisel might be drawn, after heating all over and quenching the cutting edge, by letting the heat "run out" to the cutting edge.

Tempering Colors.—To use pyrometer control with such a process is not very feasible, but fortunately nature has provided a fairly accurate means of controlling drawing temperatures. Steel oxidizes more and more readily as the temperature is raised, and the oxides formed change color with the temperature. These oxide colors are very noticeable if the surface of the steel is clean, and, by observing the changing colors, the drawing temperatures can be determined with an accuracy sufficient for average industrial purposes. Color charts are published that purport to show the correspondence between color and temperature, and drawing temperatures are often specified by color rather than by temperature. There is, however, no close correspondence between temperature and color because time has some effect in drawing, and the procession of "temper colors," as they are called, will continue even if the temperature is held constant. This probably accounts for the differences in color charts of which examples from two sources are given in the following tables. Table A is probably accurate for rapid heating,

Tempering or Drawing Colors with Approximate Temperatures

Table A

Color	Temperature	
	Degrees Fahrenheit	Degrees Centigrade
Very faint yellow	420	215
Light straw	430	220
Light yellow	440	225
Pale-yellow straw	450	232
Straw	460	238
Dark yellow	470	244
Deep straw	480	250
Yellow brown	490	255
Brown yellow	500	260
Brown	510	265
Peacock	520	270
Light purple	530	276
Purple	540	282
Dark purple	550	288
Light blue	560	294
Blue	570	300
Dark blue	600	315

Table B

Color	Temperature			
	8 minutes		1 hour	
	Degrees Fahrenheit	Degrees Centigrade	Degrees Fahrenheit	Degrees Centigrade
Faint yellow	460	238	370	188
Light straw	510	265	390	200
Dark straw	560	295	410	210
Brown	610	320	430	220
Purple	640	338	450	232
Dark blue	660	350	490	255
Light blue	710	375	510	265

Table B, for slower heating, judging from observation. The tables are of only approximate value, but the tool hardener uses colors in the light of experience and not of temperature.

HIGH-SPEED STEEL

Hardening High-speed Steel.—"High-speed steel," as the name implies, is intended for use in tools for heavy duty, duty that means high temperature. High-speed steel will retain its hardness at temperatures that would soften ordinary tool steels. This property is due principally to the presence of a considerable

FIG. 48.—Hardened high-speed steel. 500 diameters.

amount of tungsten that varies from about 14 to 17 per cent in commercial high-speed steels. Chromium and other alloying elements are also present. The critical range of high-speed steel is below ordinary temperatures, and its treatment is different from that of commercial tool steels. The development of high-speed steel and the working out of the proper treatment required long investigation in which Taylor was a pioneer. His investigation has been described at length in a work that is one of the classics of metallurgy, "The Art of Cutting Metals."

The hardening of high-speed steel requires skill on the part of the operator, because the proper time at which to remove from the furnace is a matter of observation rather than of exact temperature control. The temperature of the furnace can be

determined by a pyrometer, but the heating of a tool of high-speed steel is controlled by color or by the appearance of the surface, the proper temperature sometimes being determined by the "sweating" of the surface. Opinions differ regarding the temperature that this represents but it is probably close to 2150° F. (1175° C.), judging from observations made with optical pyrometers. Some operators state that the hardening temperature is as high as 2350° F. (1290° C.). The best description is possibly that the hardening temperature is close to the melting point.

The critical range being below normal atmospheric temperature, high-speed steel is air hardening and may be cooled in air after heating, although an air blast is used and quenching in molten lead or salts or in a bath of oil is preferred. The use of oil is common but the molten bath is more generally employed, being maintained at temperatures between 900 and 1125° F. (480 and 610° C.). A photomicrograph of high-speed steel hardened by quenching in molten lead is shown in Fig. 48.

Reheating After Quenching.—After quenching, high-speed steel should be cooled to or nearly to room temperature and then reheated to increase the hardness. Temperatures between 1050 and 1150° F. (565 to 620° C.) have been recommended for reheating, Taylor preferring 1150° F. (620° C.). A temperature too high may result in softening rather than in increasing hardness. The temperature at which high-speed steel begins to soften is ordinarily above 1150° F. (620° C.), but softening sometimes occurs at temperatures as low as 1100° F. (595° C.). For this reason, 1050° F. (565° C.) is often preferred, a temperature possible for the air furnace or for the lead bath but not for the salt bath because of the high melting point, usually 1100° F. (595° C.). Reheating is not always required. Tools intended for heavy cutting will soon be heated to a dull-red heat in service, but tools that will not be so heated should be reheated after hardening.

The molten bath is usually preferred to the air furnace for reheating, because such a bath may also be used for quenching. The lead bath has an advantage over the salt bath in the lower melting point, the use of salt baths requiring heating to 1125° F. (610° C.) at least.

Preheating High-speed Steel before Hardening.—Before the final heating in the high-temperature furnace, high-speed steel should be preheated to 1600 to 1650° F. in a separate furnace. This preheating is advisable to avoid breakage that may occur

on too rapid heating, to avoid excessive oxidation, and, also, to shorten the time at the high temperature, for if held too long, the steel will be burnt. The time during which high-speed steel remains at high temperature should be as short as possible to avoid excessive grain growth. To bring the cutting edge of a tool to the sweating point requires but a brief period of time. No high-speed tools require soaking; in fact, holding too long means a rough and, perhaps, spoiled surface, if not burnt steel. To obtain a clean surface, high-speed steel is often heated quickly to the sweating point, then removed from the furnace and brushed with a wire brush to remove scale and, finally, reheated to the sweating point for hardening. The steel should not be allowed to cool below about 1600° F. (870° C.) when brushed.

Furnaces for High-speed Steel.—The extremely high temperature required for hardening high-speed steel make special high-temperature refractories advisable. The life of ordinary commercial refractories is short in this service, and, if used, furnaces should be so designed that rebuilding will not be difficult. Much longer life can be obtained by using refractories composed largely of aluminum oxide or silicon carbide, supplied under trade names. The first cost of such materials is much higher than that of fire brick, but the actual cost will be less.

Furnaces for hardening high-speed steels are overfired or underfired, the overfired having advantages in lower cost of construction, greater speed of heating, and in requiring less fuel; and the underfired, in uniformity of heating. The salt bath, with barium chloride, is also used for heating, but the furnace is preferred because of difficulty due to decarburization in the salt bath, although the bath will heat more rapidly and uniformly than the furnace.

Equipment for Tool Hardening.—The equipment required for tool hardening will depend upon the tools to be treated and the quantities to be handled. Standard tools, milling cutters, reamers, and drills, for example, made and used in standard sizes, can be made in quantities by specialized manufacturers at a lower cost and often better than by the ordinary tool room. But sometimes special tools or tools of special size that are not easily purchased in the open market are required, and such tools will be homemade. The hardening equipment of the specialized manufacturer will differ from that of the tool room with a smaller, more irregular, and more varied output. Con-

ditions vary too much to permit any brief description of tool-hardening equipment, but in Fig. 49 is illustrated a tool-hardening room well equipped for average work. The equipment comprises a furnace of moderate size for carburizing or for hardening carbon steel, a small furnace that can be used for preheating high-

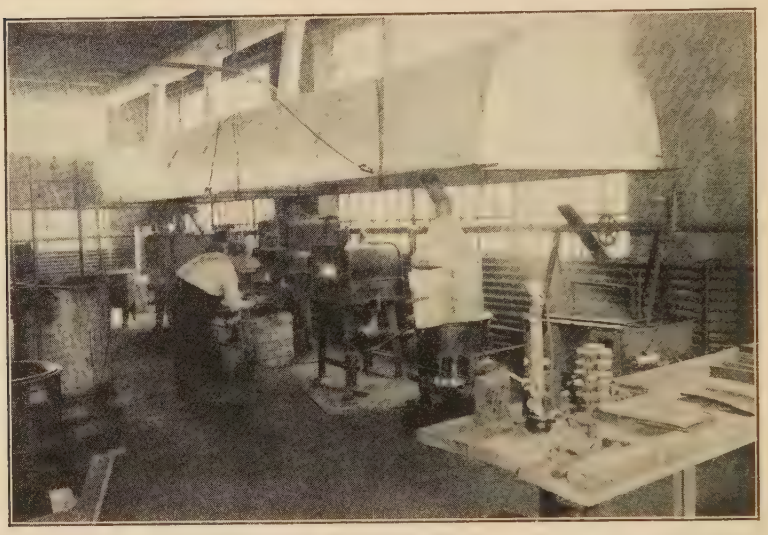


FIG. 49.—Hardening room.

speed steel or for hardening, a furnace for the final heating of high-speed steel, a lead pot for quenching and for reheating high-speed steel, an oil bath for drawing, and quenching tanks containing oil and water, respectively. To this can be added a preheating furnace for tool steel, a vertical heating furnace, and other equipment when a large or special production so requires.

CHAPTER VII

CARBURIZING

CARBURIZING COMPOUNDS AND PROCESSES

Carburizing Once a Process for Making Steel.—Carburizing is the oldest known process for the manufacture of steel. Until the present melting methods were made commercial, steel was produced by heating solid wrought iron, practically carbonless, in contact with charcoal and other substances containing large quantities of active carbon. In some way, not yet known, carbide of iron is formed and gradually penetrates the wrought iron as the process is continued. As already explained, steel is a mixture of iron and carbide of iron. The process is no longer used for the manufacture of steel but is still carried on for the purpose of obtaining a high-carbon surface on soft steel whenever the combination of a hard surface and a soft interior is desired. Heat treatment that will harden the surface will leave the interior soft.

Carburizing a Gas Process.—While there are few facts that explain the process, it is definitely known that carburizing is a "gas process." Direct contact with the carburizing material may have some effect; this cannot be proved or disproved because gas is usually present, but this is not of importance. Present-day carburizing practice depends on the use of carburizing gases. Emphasis is laid on this point because of a common impresssion that carburizing requires contact with solid carburizing materials, an impression that sometimes unnecessarily increases the cost of operation. Carburizing, carried on with commercial gas alone, is distinctly a gas process. That carburizing with the solid carburizers is also a gas process can be proved by packing two samples in the same container, one in contact with the carburizer, the other out of contact. Contact can be prevented by suspending the sample in a cage of wire screening having a mesh fine enough to prevent the entrance of the carburizer, but through which gas may pass. If, after carburizing, the samples are examined, the results will be prac-

tically identical, presuming that the specimens were heated to the carburizing temperature at the same rate. If one specimen is nearer the wall of the box, the penetration will be deeper, a point to be carried in mind.

Carburizing Described.—With this picture of a gas process, carburizing can be described as *a process for increasing the carbon content of solid iron or steel, containing little or no combined carbon, by contact with hot carbonaceous gases with the consequent formation of carbide of iron that, by some reaction or series of reactions, is produced at the surface and gradually diffused through the metal to a depth below the surface that is dependent on the temperature and time of contact and, also, upon the pressure of the gas.* The minimum carburizing temperature is that below which no reaction takes place; the maximum temperature, that above which overheating would occur. In industrial practice, the depth of carbon penetration is usually limited to a comparatively thin layer.

When more is known about the carburizing process, it will probably be possible to write a shorter and simpler definition, that given being more an explanation than a definition.

Gas Carburizing in Retort Furnaces.—Carburizing being a gas process, it is possible to pack containers much more economically than would be the case if contact with solid carburizers were required. Gas penetrates into all holes and recesses; solid particles do not. Active commercial gases are often used for carburizing, thus doing away with the expense of heating containers and solid carburizers. Natural gas, coke-oven gas, and others that contain quantities of active carbonaceous material are excellent carburizers. Some city gas can be used, but if composed mostly of water gas, containing large amounts of hydrogen, the carburizing effect will be small. Gas carburizing is usually carried on in rotary furnaces.

Carburizing Compounds. Natural Carburizers.—On account of the variation that sometimes occurs in composition of city gas, present practice continues the use of the rotary furnace, with the advantage of doing away with the container, but with carburizing compounds in place of or to supplement gas. The use of the rotary furnace is limited to parts that are comparatively small, and for this and other reasons that affect cost and operating conditions, the so-called "pack-carburizing process," using containers and solid carburizers, is more generally used. The process depends on the formation of active carburizing

gases when the carburizing compounds are heated. The temperatures employed for carburizing lie between about 1550 and 1900° F. (845 and 1040° C.) but the range for general practice lies between 1650 and 1750° F. (900 and 955° C.). Within this wide range of temperature, carburizing compounds give off active gas.

Solid carburizing compounds may be divided into two types, natural and chemical. The natural compounds are materials that in the natural state or after a little treatment will serve for carburizing. Chemical compounds on the other hand, are synthetic mixtures of carbonaceous materials and chemicals. Common examples of natural carburizing compounds are bone, leather, natural or charred, nutshells, and other animal and vegetable products. Charcoal may be included in the list but is a poor carburizer, and results obtained with charcoal alone are probably due to chemical reactions somewhat similar to those obtained with chemical carburizers. Charcoal and bone, either raw or charred, make an excellent carburizing compound, once extensively used. Such a mixture does not form a gas so "rich" as raw bone, and carburizing can be carried on with less danger of a too high carbon content in the case.

Natural carburizers can be used once, or, at the most, twice, because the active gases are driven off in the process. After use, therefore, the compound is renewed by mixing new material with the spent compound. Examples of mixtures are:

New bone, per cent	50	25	25
Used bone, per cent	50	75	25
Charcoal, per cent	..	..	50

The used bone and the charcoal aid in avoiding too much carbon in the case. Boneblack and oil form a compound intended to give a pearlite case. Being finely divided, powdered, more time is required for heating than with compounds composed of large particles.

Chemical carburizers have replaced natural carburizers because of lower cost and because natural carburizers are comparatively scarce, at least the supply is too limited to meet the demand that followed the rapid increase in manufacturing that began in the early part of this century. The supply of chemical carburizers is practically unlimited, and the cost much lower; so that the

replacement of the natural carburizers, bone in particular, was rapid.

Chemical Carburizers. Reactions.—The general use of chemical carburizers in the United States is comparatively recent, little being used before about 1910, but in Europe chemical carburizers have been used for a long time. References in technical literature and in patents indicate their use at least 70 years before introduction into practice in the United States. In spite of this long history, the chemical carburizer was offered here as at least a new development, sometimes as a secret or a patented mixture. The element of secrecy has disappeared, and materials that have had long usage are no longer protected by patents.

Chemical carburizers are composed of *fixed* carbon, with which are mixed chemicals, usually carbonates. The fixed carbon is usually charcoal, soft petroleum coke, or sometimes soft coal. Other forms of carbon, for example hard coal and hard petroleum coke, are not reactive. To the fixed carbon the common carbonates barium, calcium (lime), and sodium (soda ash) are added. Ammonium carbonate has also been used but the cost is too high for commercial practice. On heating, the carbonates give off carbon dioxide gas; this, in turn, reacts with the carbon to form carbon monoxide, an active carburizing gas. The chemical equation for this reaction is

$$C + CO_2 = 2CO$$

Carbon + carbon dioxide = carbon monoxide

The fixed carbon used must meet several requirements. It must be reasonably cheap, must react easily with the carbon dioxide, must have comparatively little shrinkage, and must be mechanically strong so that it will not break up on handling. Sometimes, cost is of more importance than the other requirements. Charcoal (hard wood) seems to be the best source of carbon, but a non-caking coal may be used to reduce cost if shrinkage is not important. Coke is also cheap but is not reactive. Coke is, however, often mixed with charcoal to lower cost and to decrease shrinkage. Although coke is inactive, this dilution has little effect, and the results obtained are, perhaps, better than with charcoal alone. Charcoal shrinks, coke does not. Charcoal is costly, coke is not.

The chemicals of the chemical carburizers, the common carbonates, are particularly adapted to carburizing, giving off carbon

dioxide at the temperatures employed in the process and taking it up again when cold, so that the compounds are regenerative and can be used again many times. The reactions are simple:

$$CaCO_3 + \text{heat} = CaO + CO_2$$
$$\text{Calcium carbonate} + \text{heat} = \text{lime} + \text{carbon dioxide}$$
$$CaO + CO_2 = CaCO_3$$
$$\text{Lime} + \text{carbon dioxide} = \text{calcium carbonate}$$

The first reaction is important in the manufacture of lime from limestone. The carbonates of barium and sodium go through similar reactions in the process. The regeneration of the carbonates, the second reaction, requires time, and compounds that have been through the carburizing process must be allowed to stand for several hours before using again. Neglect of this has been responsible for trouble.

Composition of Commercial Chemical Carburizers.—Carburizing compounds may contain one, two, or all three of these carbonates, although calcium carbonate, being the cheapest, is usually a component. The following table shows some examples of the wide variety of chemical carburizers that is possible:

Composition of Typical Commercial Chemical Carburizers

1. Barium carbonate (powdered)	50	This is unnecessarily high in barium and too dusty. Has been used but little in the United States
Charcoal (powdered)	50	
2. Barium Carbonate (powdered)	15 to 18	A more common barium compound
Charcoal (granulated)	85 to 82	
3. Barium carbonate	5 to 6	A typical compound containing the three carbonates
Soda ash	5 to 6	
Lime	5 to 6	
Charcoal	85 to 82	
4. Soda ash	12	
Charcoal	88	
5. Lime	12	
Charcoal	88	
6. Lime	6 to 8	These are representative proportions; lime being cheaper, less soda ash would be used
Soda ash	6 to 4	
Charcoal	Balance	
7. Lime	6 to 8	
Soda ash	6 to 8	
Coke	35 to 40	
Charcoal	Balance	
8. Barium carbonate	7½	A very successful commercial mixture. The soda ash is kept down on account of its action on alloy-carburizing boxes
Lime	7½	
Soda ash not over	5	
Charcoal	40 to 45	
Coke	35 to 45	
9. Lime	8	Various combinations are used, but coal coke is more commonly used on account of its lower cost
Soda ash	6	
Charcoal	50	
Petroleum coke	36	

Composition of Typical Commercial Chemical Carburizers (*Continued*)

10. Lime	2	This will carburize as well as compounds containing more chemicals; coke may be added
Soda ash	2	
Charcoal	96	
11. Soft coal (non-caking)	80	These are representative soft-coal mixtures; the coal is sometimes used in powdered form, sometimes in small granules
Lime	15	
Soda ash	5	
12. Soda ash	15	
Lime	25	
Soft coal	60	

Factors Governing Carbon Content and Penetration.—In spite of differences in composition, the depth of penetration will be practically the same for all compounds under similar operating conditions. To this there is one exception: powdered compounds require more time than granular compounds for the same depth of case because the rate of penetration of heat is slower. This, however, is a mechanical condition rather than one of composition. The carbon content of the outer portion of the case will not vary greatly because of composition unless the amount of carburizing gas given off is very large or very small. The carbon content seems to depend upon the richness of the carburizing gas. Compounds can be so made that the carbon content of the case will not exceed 1.05 per cent, a so-called "pearlite case," for which there is some demand for carburizing parts to be ground after hardening.

Bone and charred leather, natural carburizers, have been used as the carbon base of chemical carburizers, but to no great extent. Similarly, the carbonates have been replaced by other chemicals, for example calcium saccharate, a by-product in the manufacture of sugar, and portland cement, a rather expensive source of lime. Cyanides and ferro- and ferricyanides were once suggested but have not been used because of cost and, also, because poisonous.

Manufacture of Chemical Carburizers.—The manufacture of carburizing compounds for commercial use requires more than simple mixing of the ingredients, but in the early stages of the use of chemical carburizers in this country, mixing was often a simple process. Sometimes the chemicals were placed in the bottom of the container, and the charcoal on top, but this was unsatisfactory, especially if the temperature of carburizing was high enough to melt soda ash, usually present. Simple mixtures of charcoal and chemicals would carburize satisfactorily, but

when shipped, the chemicals would usually drop to the bottom of the container. Such mixtures were also difficult to handle on account of the dust.

The present demand is for uniform, permanent mixtures, and to obtain this a binder is required, of which molasses and water is an example. Even water will serve as a binder provided that the mixture is kept wet, and mineral oil is also used. The most important service rendered by a binder is the prevention of dust, extremely disagreeable, if not dangerous, to the workmen. Barium carbonate is poisonous.

The ingredients of chemical carburizers can be mixed by hand, but a mechanical mixer, for example a cement mixer or a similar revolving drum, is preferable. Charcoal, coke, chemicals, and binder are all mixed together. This is the standard method, but others have been employed. The charcoal granules can be sprayed with a water suspension of the chemicals, which may also be a solution if soda ash, soluble in water, is employed. Or charcoal may be soaked in a solution of soda ash, which will be absorbed. Impregnation, of which this is one example, is sometimes favored, and water-soluble salts of barium and calcium, the chlorides, may be used to impregnate. After the charcoal has absorbed the solution, the chlorides are converted into carbonates by the addition of a solution of soda ash. The charcoal is then impregnated with the carbonates of barium or calcium or both, soda ash, and salt, as a result of the reaction. Impregnated compounds are not extensively used.

Instead of mixtures such as described, compounds may be formed by binding the chemicals and charcoal together in pills or briquettes. By partly coking an intimate mixture of powdered coal and chemicals briquettes can be made. Even better mixing is obtained in the manufacture of one compound that takes advantage of the distillation of creosote, the residue being coke. The carbonates are added to the liquid before distillation and remain, thoroughly mixed, with the coke. Such compounds have been used, but preference is usually given to the mechanical mixture for reasons of cost, supply, and handling.

Points in Selecting a Carburizer. Carbon Content of the Case. Pearlite Case. Rate of Penetration. Weight.—The requirements of the users of commercial carburizers vary, and variation may, therefore, be expected in carburizers. The item of general importance is cost, and the carburizer that will give

the results desired at the lowest cost is the one that will usually be chosen. There are, however, other conditions that must be considered in making a choice, and, therefore, the cheapest composition is not always the one to be used. The individual user may be interested in only one or two points about a carburizer, but in order to make an intelligent selection, it is necessary to know how the composition and condition of a carburizer affects the results and the cost. The principal points to investigate are

Fig. 50.—Carburized steel; excess carbide or hyperentectoid case near surface. 100 diameters.

The carbon content of the case.
The rate of penetration.
The weight of a given volume.
Regenerative power.
Shrinkage.
Mechanical strength.
Cleanliness.

The carbon content of a case naturally decreases toward the core, but this decrease is apparently not gradual, rather in steps. In Fig. 50 is pictured an average case that consists of three layers—the outer, which may contain as much as 1.25 per cent of carbon; a pearlite layer; and a third layer in which the carbon content becomes lower as the core is approached. By control of the process or with special compounds, the formation of excess cementite can be avoided and a *pearlite case* formed, as illustrated in Fig. 51. The presence of excess cementite is not necessarily harmful, but it is often responsible for cracking on grinding, and, therefore, a pearlite case is sometimes preferred. A high-carbon case will be formed if the carburizing gases are rich, if the penetration is deep, and if the

carburizing temperature is high. The presence of hard carbide of iron—cementite—around the grains, as in Fig. 50, is often undesirable. This can be prevented by heat treatment, which will be described later.

Carburizing compounds that will not form a case with carbon above the pearlite point are usually in powdered form and, therefore, slow. Such compounds are not rich in carburizing gases. Bone-black, powdered charcoal, and similar substances serve as the carbon base. Carbon can be kept down in granular compounds by using only small amounts of chemicals, perhaps 1 to 2 per cent, and by diluting with inert material—coke, for example.

The rate of penetration, governing the time required to obtain a desired depth of case, depends upon the size of the particles more than upon the composition, although it is possible to make compounds so weak that the penetration will be slow. The size of the particles affects the rate of heating to temperature, so that large particles are preferred to small. A difference in the rate of heating can be observed with rather small difference in size, between four and six mesh for example.

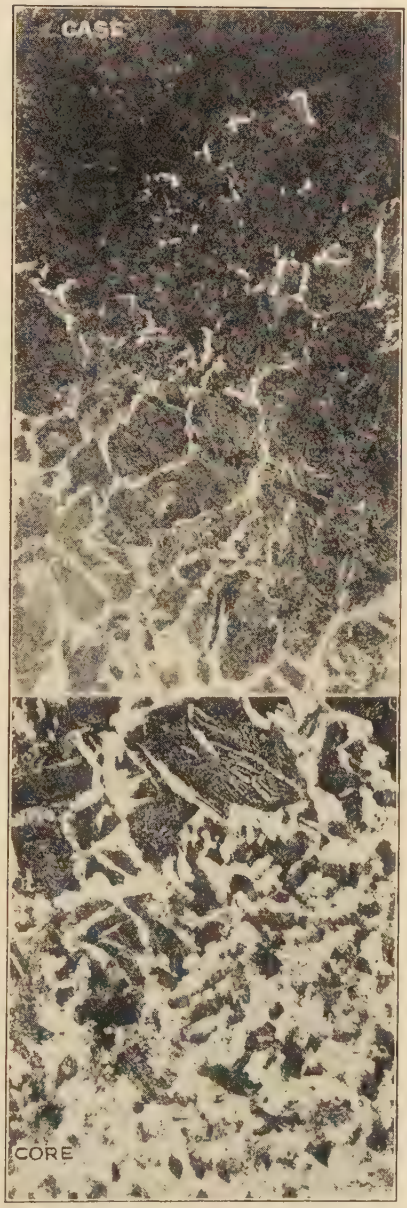


FIG. 51.—Carburized steel. Pearlite case. 150 diameters.

The weight of a given volume of carburizer affects the first cost because carburizers are sold by weight but are used by volume. The weight of a carburizer will depend upon its composition and upon the size of the particles, and the amount, by weight, required to fill a carburizing container or box will, therefore, differ with different carburizers. For this reason, a compound costing $100 a ton may be cheaper than one costing $50 a ton. If it costs 50 cts. to fill the container with compound costing $100 a ton and 60 cts. to fill it with compound costing $50 a ton, the $100 compound will be cheaper. The yardstick is the cost of filling the box, not the cost per ton, and it would be better practice to sell carburizers by the bushel or the cubic foot. Price per ton must always be converted to price by volume, the cubic foot being a convenient unit.

Comparative Cost of Carburizers. Effect of Weight, Shrinkage, Mechanical Strength.—The actual cost of a carburizer is affected most by its ability to be reused, and a compound that can be used many times may be cheaper than one that can be used only once or twice, although the latter may have a lower first cost. The comparatively low cost of the chemical carburizers is due to their regenerative power; they can be used over and over again.

Another item that enters cost is shrinkage, loss in process, perhaps by burning. Shrinkage is also of importance in carburizing, because it may be necessary to keep the parts being carburized well covered. Carburizing being a gas process, actual covering of the parts is not necessary, provided they are surrounded by carburizing gases. Sometimes, however, containers are not gas tight, and the parts within may, therefore, need a cover of compound, which might be removed by shrinkage. New charcoal shrinks considerably on heating and is, therefore, sometimes preheated before putting into a compound, although the addition of coke will often make preshrinkage unnecessary. Coke is not affected by heating within the container. Soft coal, sometimes used for the carbon base, has a large amount of shrinkage, but this can be reduced by mixing with coke or with the soft-coal compound that has been in service.

Compounds for general service must have mechanical strength, so that they will not crumble in service or on handling. Lack of mechanical strength is often a cause of high shrinkage. Compounds to be reused must not break up easily, because the loss on handling will be high, increasing the cost.

Mechanical strength also affects the cleanliness of a compound, for one that breaks up easily will produce much dirt. Cleanliness is an important item, because a carburizer is not a pleasant material to handle at best. Such chemicals as lime, soda ash, and barium carbonate in powdered form can be very unpleasant, to say the least. To hold these chemicals as well as small, dusty particles, binders, for example molasses, are commonly used. Such binders are lost on heating, and used compounds will, therefore, be dusty. It is good practice to dampen used compound with water or, better, with a small amount of oil if waste oil is available. This will prevent loss in handling and make handling much easier.

A Unit for Determining Actual Cost of a Carburizer.—The actual cost of a compound depends upon its weight per a given volume, its regenerative power, and the loss in service due to shrinkage or handling. A convenient unit for determining the first cost is the cubic foot, and compounds should be valued by cost for a cubic foot. Part of this cubic foot must be replaced because of loss in service, the actual cost depending upon the amount replaced. This presumes the compound to be regenerative or to be used partly new and partly old. The actual cost of a compound is, therefore, the replacement cost of a cubic foot, a convenient unit.

The use of such a unit can be illustrated by an example. A compound costs $100 a ton, and 1 cu. ft. weighs 50 lb. One ton is, therefore, 40 cu. ft., and the first cost is $2.50 per cubic foot. After a number of heats, the loss is found to average $\frac{1}{5}$ cu. ft. for each heat. The replacement cost is, therefore, $0.50 per cubic foot. Another compound costs $120 per ton, and a cubic foot weighs 50 lb., so that there are 40 cu. ft. in a ton, the cost being $3 per cubic foot. The average loss per heat is 15 per cent, and the replacement cost per cubic foot is, therefore, $0.45. The actual cost in service of the second compound is lower than that of the first, although the first cost is higher. Put into a formula,

$$\frac{\text{Price per ton}}{\text{Cubic feet per ton}} = \text{price per cubic foot}$$

$$\text{Price per cubic foot} \times \text{percentage lost} = \text{replacement cost (per cubic foot)}$$

The loss on initial heating is always higher than the loss on subsequent heatings, and the percentage lost in service and in

handling should be determined by striking the average loss for a number of runs.

CARBURIZING PROCESS

Pack Carburizing.—The carburizing process can be described briefly as a process for obtaining a high-carbon surface on low-carbon steel by heating in contact with carburizing gases at a desired carburizing temperature for a period of time long enough to obtain the depth of penetration desired. The process carried on with gas alone is called "gas carburizing." If solid carburizing compounds are used in which the steel parts are packed, the process is called "pack carburizing."

Pack carburizing is carried on in containers in which the parts to be carburized are packed with carburizing material. After covering and sealing, the container is placed in the furnace, heated to the carburizing temperature, and held at that temperature for the length of time necessary to obtain the required depth of case. When the process has continued long enough, the container is removed from the furnace and allowed to cool before opening, unless the parts are quenched direct from the container, a method that will be discussed later. After cooling, the contents of the container are dumped, and parts and carburizer separated by hand or by a sifting device. The carburizer is then stored for regeneration if a chemical carburizer.

Before the carburizer is to be reused, sifting to remove dust is advisable for cleanliness and, also, to avoid loss of time in heating. The dust may be removed before or after storing. Chemical carburizers require time for regeneration and are, therefore, stored for several hours, usually overnight, before using again. After regeneration, the used compound is mixed with enough new compound to make up for the amount lost in process and handling, and this mixture is then ready for further packing.

Depth of Case.—The pivot around which the carburizing process turns is the depth of case, this being usually the only specification employed. A "one-sixteenths case" is a familiar form of expression. The amount of case required will vary from a thin skin to $\frac{1}{8}$ in. or more, but the amount necessary will be specified for two reasons: one, to indicate how much is necessary; the other, to avoid getting more than necessary. If toughness of the core is wanted, the case must be shallow, and the process must be closely controlled. With heavy parts, the

depth may not be of so much importance, but the deeper the case the greater the cost. Control of the depth of case is necessary from the standpoint of service and of cost.

The depth of case obtained in carburizing depends on two factors, temperature and time. The penetration will be deeper the longer the process is continued, and more rapid as the temperature is increased. Increase of temperature would, therefore, appear advisable in order to save time, but the danger of overheating and the rapid deterioration of furnaces at high temperature set a limit to carburizing temperatures. Carburizing is sometimes carried on at temperatures as high as 1850° F. (1010 ° C.), but in average practice, temperatures between 1650 and 1750° F. (900 and 955° C.) are employed with 1675 to 1700° F. favored. Higher temperatures are not dangerous if the carbon content is very low, in the neighborhood of 0.10 per cent.

A third factor—pressure—also governs the rate of penetration, because an increase in the pressure of the carburizing gas will shorten the time required to obtain a desired case. Carburizing under pressure is not new—one of the first patents covering carburizing under pressure was issued in 1867—but has not been applied to general industrial practice because of the difficulty of obtaining uniform pressure and, also, because the cost of equipment and control will increase the cost of carburizing beyond the amount saved by reducing the time.

Control of Depth of Case. Test Pieces.—In practice the carburizing temperature is fixed, and the furnace is maintained at that temperature. In order to obtain a desired depth of case, carburizing is carried on at constant temperature for the length of time required, this being determined by trial. Furnace design and pyrometers have made possible uniform temperature and close control, so that similar lots may be carburized alike by time. With varying conditions, however, even close and accurate temperature control will not always insure the exact depth of case desired. Small lots will be heated more quickly than large lots, and the temperature of the furnace at the start will seldom be the same. Some operators, therefore, consider only the time elapsed after the pyrometer indicates the required temperature. But this does not take into account any variation in the time of heating, and to include this some depend upon the curve drawn by a recording pyrometer. Furnaces, however, are not always uniform throughout, variations in heating

are not easily followed, and pyrometers do not necessarily show the temperature of the work in process. In spite of variations, close control is possible by the use of test pieces that are packed with the work and removed at intervals for examination.

The use of such test pieces is a practice of long standing, a safeguard in operation before the days of pyrometers and uniform furnaces. In spite of a rather common impression, such test pieces do not need to be of a size to match the parts carburized nor necessarily of the same steel, although this is sometimes advisable. Time and temperature control and rise of temperature in a container will be uniform regardless of the size of the parts within. Some common sense in placing the test piece is necessary, and it is then possible to use small pieces that are convenient to handle. The test piece must not be so small that the entire cross-section will be carburized. The core should cover about one-third of the area at least in order to permit measuring the depth of case. A convenient size for test bars is $\frac{1}{4}$ in. round or its equivalent, unless the depth of case is greater than $\frac{1}{16}$ in.

After removal from the container, the test piece is allowed to cool below the critical range and is then hardened. Cooling in air is preferred to quenching from the container, because the case can be more easily distinguished from the core after breaking. The depth of case can be determined by examining the fracture and can be measured quite accurately with a magnifying glass and scale. The microscope for measuring the size of Brinell impressions, which is equipped with a scale, can be used for the purpose. The case can be brought out sharply by dipping the surface of the fracture in 10 per cent nitric acid in water, but this etching will prevent measurement with a magnifying glass.

For close control, particularly of carbon, unhardened test pieces should be examined occasionally, at least, under the microscope. Carbon can be determined by analysis of chips turned off in the lathe, but examination with the microscope is more convenient and sometimes more accurate. The microscope may not tell the actual percentage of carbon so accurately as chemical analysis, but it will give better information about excess carbide of iron. The depth of case can also be measured with the microscope, although there is some difference of opinion about locating the point at which the case ends. This is usually considered to be the point at which the pearlite and ferrite are equal in amount, approximately 0.40 per cent carbon. For such

microscopical examination, unhardened samples, cooled in the box, should be used.

Success in carburizing, depends on continued, accurate control of temperature uniformity in heating, and uniformity in carburizing temperature. For this, furnace design has been improved, accurate pyrometers have been developed that include automatic controlling instruments, and operating methods have been worked out.

Quenching Direct from Container.—Reference has been made to two methods of cooling after carburizing—in the container and by quenching from the container. Quenching direct from the container is, however, more than a method of cooling; it is a heat-treating process, although part of the carburizing process rather than a separate heat treatment. Direct quenching is a practice of long standing and one that has often been criticised as bad practice, but rather from mistaken theory or because the method was not carried on properly. Much of this criticism was aimed at hardening by direct quenching without subsequent treatment, but it has also included direct quenching followed by rehardening. The argument against direct quenching usually states that the temperature of carburizing is well above the refining temperature of both cases and core, and, therefore, both will be of coarse grain if so treated. Coarse grain structure is often responsible for trouble in service and should, therefore, be avoided. Under some conditions, this argument may be true, but, on the other hand, parts that have been hardened by quenching direct only have given good service for years.

If failures of parts quenched direct are analyzed, insufficient hardness will be found responsible for many; overheating in carburizing, for others. Parts that are very thin can be hardened by quenching direct because the rate of cooling is rapid, but heavy parts cool more slowly and, therefore, may not be hard enough. Quenching direct without rehardening is sometimes desirable for thin parts, for example the head shell of a bicycle, part of the bearing in the handle bar. This is pressed into place and, if rehardened, may be too brittle for pressing. The spinning ring is another thin part that is frequently hardened by quenching from the carburizing container without further treatment.

Quenching direct will improve the condition of the case and, also, of the core, provided that the carbon content of the core is not above about 0.20 per cent. Separation of cementite around

the grains in the case is prevented, quenching direct being practically a normalizing treatment. As already explained, large grains surrounded by cementite are not easily broken down at the normal hardening temperature. If the carbon content of the core is less than 0.20 per cent, quenching direct will result in a tough core having a fracture fibrous in appearance if broken for examination. Steel containing over about 0.20 per cent of carbon will not be so tough as steel of lower carbon, because of the higher carbon content. Such steel has a refining temperature below the carburizing temperature. On the other hand, the refining temperature of the lower-carbon steels is not far from the carburizing temperature. Low-carbon steel is, therefore, preferred for carburizing and can be quenched direct with excellent results, provided that the carburizing temperature is closely controlled and not too high.

Double Treatment for Core and Case.—Another form of treatment connected with carburizing and termed "double treatment" overcomes the results of carburizing at too high temperature and normalizes and refines the case and core. After carburizing and cooling in the container, the carburized parts are heated to the refining temperature of the core and quenched, a treatment that breaks up the cementite around the grains of the case and refines the crystalline structure of the core. In general practice, double treatment is usually avoided by control of the carburizing temperature. Such control is much less expensive than extra treatment. High temperature in carburizing is usually responsible for a high carbon content. This means a large grain surrounded by cementite, a structure that is not easily refined. In modern practice, double treatment has largely been repaced by quenching direct from the carburizing container. For such treatment, a low carbon content is advisable, the range from 0.10 to 0.20 per cent carbon being preferred.

Quenching direct and double treatment may prevent the formation of grains surrounded by cementite, but they do not prevent the formation of that structure on subsequent reheating. If the temperature of reheating is high enough and is followed by air cooling, excess cementite will form around the grains, and the fracture will be coarse. Forging, for example, is sometimes required after carburizing, and the heating operation will destroy the result of any previous treatment. A pearlite case would be preferred.

CHAPTER VIII

CARBURIZING *(Continued)*

EQUIPMENT AND HANDLING

Pack Carburizing Operations.—Carburizing in containers (pack carburizing) is a process that requires a number of operations for production and for preparing the carburizer as well. Carrying on the process also requires considerable equipment such as containers, tools for packing and for handling, and, also, separating and cleaning devices for the carburizer. The development of equipment for saving labor and handling has been slow as compared with the progress that has been made in other processes of steel treating, but new methods are now being rapidly introduced into carburizing practice. The rotary-retort furnace, for example, has been extensively introduced, after a long period of waiting, to replace the carburizing box. Automatic and semi-automatic equipment aids in cleaning and packing.

The operations of pack carburizing, described to indicate the handling and the equipment that is necessary, are as follows.

Pack parts in container with mixture of new and used carburizer.
Place cover on container and lute with clay.
Test for depth of penetration in advance of removal.
Remove container from furnace.
Cool.
Dump contents and separate parts and carburizer.
Remove containers to storage or packing room, transfer parts to next operation, remove carburizer for cleaning.
Screen and clean carburizer, then store.
Remove new and used carburizer from storage, mix, transfer to packing room.

Individual practice will vary from this. Test pieces will not be required if the process can be controlled by time, particularly if the depth of case can vary. If quenching direct is practiced, the parts and carburizer will be separated by dumping on a screen or grating or will be dumped together into the quenching tank and separated later, the carburizer being recovered unless too cheap to save.

Carburizing Containers, Materials and Design. Cast Iron, Steel, Alloys.—The most important piece of equipment required for this process is the container or carburizing box for which various materials are used. Containers differ in size, shape, and design as well as in composition, such differences being important because of the effect upon handling methods and operating cost. The cost in service of containers, however, depends upon the life, which, in turn, depends upon the material of which it is composed and upon the design.

Carburizing boxes were first made of cast iron—grey iron—the best material then available. Because iron foundries are always at hand and because of its comparatively low first cost, grey iron is still used to some extent. The life of a grey-iron box is, however, relatively short, and, furthermore, grey-iron boxes often crack in service with resulting leaks, so that this material may be actually more costly than other of higher price but more durable. Carburizing boxes have also been made of another form of cast iron—white cast iron. Although the material is hard and brittle as cast, the boxes are soon malleableized during carburizing. The advantage over grey iron in longer life is small, hardly enough to balance the disadvantage of brittleness. Few, if any, boxes are now of white cast iron.

The life of carburizing boxes was lengthened by a change from cast iron to steel. Steel castings were once more difficult to make than now, one reason for the long-continued use of cast iron. Early failures with cast-steel boxes were common because of unsound castings and, also, because of a lack of knowledge of the requirements of design, but such causes have been largely removed, and the cast-steel box is standard. A further development in the use of steel for carburizing boxes is the pressed-steel box drawn from comparatively thin sheet. Light boxes of pressed steel heat through more rapidly than the heavy cast boxes but are, of course, short lived, used once or twice and thrown away. Steel in another form—pipe—has been long used for carburizing boxes. One end may be closed by welding, or caps may be screwed on, requiring provision for the escape of gas to avoid an explosion, but covers are usually discs luted with clay.

Steel boxes have a much shorter life than boxes composed of alloys, particularly alloys of nickel and chromium. With these elements others, for example iron, may be combined. Such alloys cost five to ten times as much as steel and, therefore, must

last proportionally longer. The large investment for any considerable number of alloy boxes is a disadvantage if the capital can be better employed, the interest charge alone being a large item. Idle time adds to the expense, and alloy boxes should be working as much as possible. Quenching direct releases the box for further service, but if the box is allowed to cool before dumping, the time required will be lost, and here the steel box will have an advantage. Alloy boxes have thinner walls than steel boxes and can be heated a little more rapidly than steel boxes and are also lighter in proportion. That they are

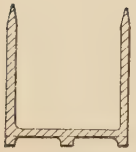


FIG. 52.—Wear at open end of carburizing box.

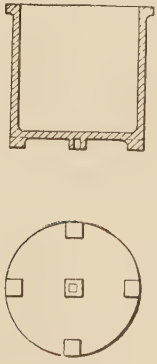


FIG. 53.—Carburizing box.

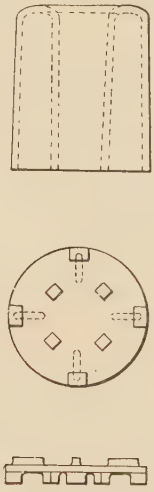


FIG. 54.—Carburizing box. "Upside down" type.

attacked by soda ash in carburizers is only a slight disadvantage that can be avoided by using other chemicals or but little soda.

The wear of a carburizing box is due principally to oxidation to which steel is much more susceptible than the alloys that are used. Some portions of the box, however, are more exposed than others, particularly the open top and the lugs upon which the box stands. The life of a steel box can be increased by adding a flange at the top and by making the lugs large enough to last as long as the rest of the box, and this is also true of the alloy box, although not so important. Without a flange, the top of a steel box is soon reduced in thickness, as illustrated in Fig. 52. The box of Fig. 53 is properly protected at the top,

and the supporting lugs, added to lift the box proper off the floor, are large and are provided with generous fillets. Sharp corners have been avoided because they will soon disappear and, also, because they are likely to be the starting point of cracks.

Box covers are easily replaced and at less expense than boxes, a reason for the *upside-down* box illustrated in Fig. 54. This box is packed in the regular way, the top is put on and luted with clay after inverting the box. The tube type illustrated is convenient for large bevel gears. Less carburizer is needed and heating is more rapid than in the conventional box. Another box of special design is shown in Fig. 55. This is intended to hold shafts in a vertical position to avoid warping. The extension near the top provides a rest for a steel plate through which

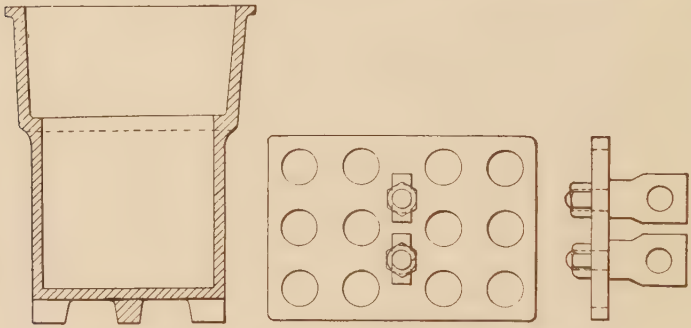


FIG. 55.—Carburizing box and fixture for shafts.

holes are drilled to accommodate the shafts. Carburizing compound fills the portion above the plate, none being required in the lower part, as the gases enter through the holes in the plate.

Shape and Size of Carburizing Containers.—Such special shapes are occasionally required, but the carburizing box is usually round or rectangular in cross-section. The shape selected will depend, to some extent, upon the shape of the parts to be treated, but the operator is usually free to choose. Cylindrical boxes are more easily spaced than rectangular boxes, but choice will depend upon comparative costs or, perhaps, upon the ease of the handling, also.

Shape may not be of so much importance as size. Large parts will require large boxes, and small parts may be most easily handled in small boxes, but, for the average, boxes may be of any size as far as filling them is concerned. In the hardening

room operated by one or two men and treating parts of moderate size, handling equipment may be limited, and small boxes, therefore, preferred. On the other hand, a large production may be handled most easily in boxes of some size, suitable handling equipment being provided. Large boxes are more economical than small from the standpoint of heating because less material in proportion to paying load will be required, but, if too large, this gain will be offset by the long time needed to heat through. This difficulty, however, can be avoided by keeping one dimension comparatively small. A box may be long and wide but, if not too high, the rate of heating need not be slow.

The economical shape and size of a carburizing box is determined by the production that can be obtained and in connection with the dimensions of the furnace as well as the size and shape of the parts to be treated. In average production, more than one kind of box will be required, and the problem of selection can be simplified by using *cut outs* made to scale to represent parts, boxes, and furnace, thus making the necessary comparisons between the different combinations possible.

Equipment for Handling Containers.—The carburizing container must be moved from one operation to another, and handling equipment must be provided. Such equipment is particularly necessary for the handling of hot containers but may, perhaps, be more necessary for saving time and labor in all the handling required. The simpler tools for handling are tongs and forks for lifting and moving and, also, the buggies for unloading and loading furnaces. Forks and tongs can be suspended on a hanging chain or rod, as illustrated by the simple hanger of Fig. 56. The lower end of the hanging bar is provided with holes at intervals to permit changing the height of the fork. Containers can be moved if the hanger is suspended from a monorail. Figure 57 illustrates a pair of swivel tongs for moving and dumping cylindrical boxes, as in quenching direct. A simple buggy for unloading and loading is illustrated in the photograph of Fig. 58. Such buggies may have one or two tongues for lifting. Either casters or small wheels are attached for rolling.

FIG. 56.—Fixture for suspending tongs.

Forks and tongs are used to bring the individual box to the furnace or to remove it, the buggy to load and unload, but

Fig. 57.—Swivel tongs.

Fig. 58.—Buggy for charging. Transfer table.

the buggy may also serve for transfer when the furnace hearth is at floor level. But moving individual boxes in any such way requires labor that can be saved. The simplicity of handling the charge with buggies may have its advantages and be a reason for having the hearth at floor level, but boxes are in the way when scattered over the floor. Preference, however, is generally given to having the hearth about 30 to 36 in. above the floor because easier for the operator, permitting moving a number of boxes at a time by means of a transfer table, illustrated in Fig. 58, or a charging truck, occasionally used. A table such as that illustrated is inexpensive, being built of angle iron or pipe and placed upon casters or wheels. The top may be of steel plate. Plate, however, will warp and, therefore, is frequently replaced by common brick held in place by a flange of angle iron and supported by strips. The table illustrated in Fig. 58 is so constructed.

These few simple tools have been described because fairly representative of the many kinds of tools in carburizing service. Each plant has its own handling problems that are met by various kinds of mechanical equipment and combinations of tools. Some processes are not carried on easily with simple equipment, but usually some combination of the tools described will permit rapid easy handling. Quenching direct is one example, requiring withdrawal of the box from the furnace and dumping in practically one operation. Handling can be simplified by providing a transfer table at the door, swivel tongs, and car tanks. Speed will be gained by using two pairs of tongs and two car tanks, with boxes between the table and tanks provided with a grating to catch the parts and through which the carburizer drops into the box.

Rotary Retort and Continuous Carburizing Furnaces.—These methods and tools apply to stationary furnace practice. Continuous furnaces may require somewhat different methods. One reason for carburizing in continuous furnaces is ease in handling. Mechanically operated furnaces, however, do not always mean lower cost, although, perhaps, easier to load and unload With proper planning and the right equipment, stationary-furnace practice need not require an excessive amount of labor or a high labor charge. But the stationary furnace cannot compete with the rotary retort furnace in cost. The retort furnace does away with the separate carburizing box and the equipment required

for handling. Loading and unloading is simple and no packing is required. The rotary retort furnace has been in service for a long time but to no great extent until recently. Although the carburizing box will remain in extensive use for some time, the retort furnace is rapidly extending its field to replace it. Carburizing practice as a necessary evil has not always received the attention which it deserved, particularly from the standpoint of labor-saving equipment and methods. Labor saving equipment does not necessarily require a complete change of equiment; often only a few simple devices is all that is needed.

Preparation of Carburizer. Cleaning and Storage.—After passing through the carburizing process, the used carburizer requires preparation for further service. The dust must be removed because troublesome in packing and because its accumulation will lengthen the time required for heating. Used carburizer must be stored to regenerate, as described in the previous

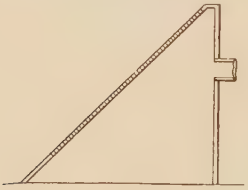


Fig. 59.—Screen for separating.

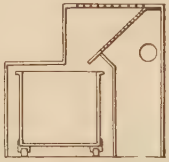


Fig. 60.—Carburizer separator and cleaner.

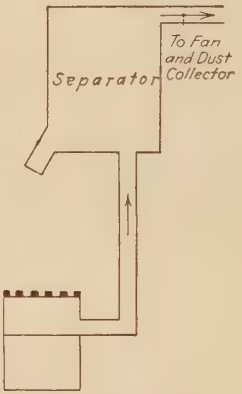


Fig. 61.—Automatic carburizer separator and cleaner.

chapter, and while awaiting further service. Used carburizer is commonly cleaned by screening. Ash sifters or other similar cleaners will take care of a small amount of carburizer, but with a large production, cleaning is generally accomplished by throwing the carburizer against a sloping screen, as illustrated in Fig. 59, over which it rolls to the bottom and through which the dust falls. Air blown through a perforated pipe placed at the bottom of the screen removes dust easily. More elaborate equipment is sometimes used, designed to avoid the scattering of dust. In Fig. 60 is shown a screen attached to a closed box into which the dust falls. Figure 61 illustrates a still better method, one that has given excellent results. Separating of parts and carburizer is combined with the cleaning of the carburizer. The equipment

consists of a box on which is placed a grating to separate parts and carburizer, a separator, a fan, a dust collector, and connecting passages. The carburizer drops through the grating and is drawn into the separator by the suction of the fan. Baffle plates separate the carburizer, which drops into the bottom of the separator, from the dust, which is carried to the dust collector or may be carried to the stack of the power house. For the treatment of a large amount of carburizer, this method is more satisfactory than screens, ash sifters, grain separators operated by hand, and other similar devices.

After cleaning, the used carburizer is stored until required again for service. When required, it is mixed with new before sending to the packing bench either by hand or in a mixer. The amount of new added is the same as the loss in service and cleaning. This loss will vary from 15 to 20 per cent when cooling in the container is practiced but may reach 50 per cent when the contents are quenched direct from the box.

Packing Containers.—The next step in the process—packing—is an operation that sometimes requires care, but ordinarily parts and carburizer may be mixed together and packed at random. This is contrary to a popular opinion that all carburized work should be spaced when packed. Close contact of flat surfaces may prevent carburizing, but the gases easily penetrate even tiny cracks. Systematic packing may sometimes be necessary to avoid distortion or contact between surfaces, but random packing is usually all that is required. As many parts as possible should be packed, this being the best rule to follow. Leaky boxes have been responsible for troubles thought due to the method of packing. While packing, the box should be jarred at intervals to permit the contents to settle. Packing is completed by adding the cover and luting with clay—fire clay or other clay that will not crack on heating. Local clays are sometimes more satisfactory than a more expensive imported product.

Cooling and Storage Space.—The storage of containers and of carburizer requires space, and room must also be provided for cooling hot containers. The provision usually made will be discussed in a later chapter but because sometimes closely connected with handling will be briefly considered here. Space may be provided in the heat-treating building or in sheds attached if there is ample ground space, or a basement may be used, but a

balcony will simplify handling, particularly if the system of Fig. 61 is used for cleaning, the separator being placed on the balcony. Gravity will carry the prepared carburizer to a packing bench below. Excess labor will be small, however, if packing can be carried on close to the furnace with storage and cooling spaces close by.

SELECTIVE CARBURIZING

Copper Plating and Coatings.—When a piece of steel goes through the carburizing process, all surfaces are carburized unless provision is made to prevent contact with the carburizing gases. Such contact can be prevented by two methods—plating with copper and packing with some protective material. Carburizing only a part of the surface is known as "selective carburizing." Selective carburizing is sometimes desirable to permit machining after the part has been through the carburizing and hardening processes or to permit straightening after hardening.

The choice between the two available methods depends upon the equipment at hand, but even more upon comparative cost. Copper plating is generally preferred because usually cheaper. The entire surface is plated and the copper is then removed from the surface to be carburized by machining or grinding. If two machining or grinding operations are required—roughing and finishing—removal of the copper requires no additional expense. The rough machined or ground surface is plated, and the copper removed from the surfaces to be carburized by the finishing operation. The copper-plating tank is often placed between the roughing and finishing machines. Either acid or cyanide copper may be used, but acid plating is probably better. Thorough washing in running water is necessary after plating to remove the copper solution, which is held by the spongy deposit. Copper will be deposited on the cleaned surfaces during carburizing unless all the solution is removed, thus preventing carburizing. Nearly all trouble that occurs in carburizing copper-plated parts is due to incomplete washing. The accumulation of copper salts in a still bath will soon cause trouble, and running water should be used.

Carburizing may also be prevented by covering the surface with a protective coating of clay. Clay, however, is easily cracked,

permitting access of the gases to the surface, so that prepared pastes are sometimes preferred. A typical paste contains

	Per Cent
Zirconium oxide (zirkite)	40
Clay (kaolin)	40
Water glass (sodium silicate)	20

This paste, on heating, forms on the surface a tight, enamel-like coating that is easily removed by washing. Clay and sodium silicate are common ingredients of pastes for selective carburizing.

No attempt has been made here to describe in detail the equipment and methods used in carburizing because of the space required and because such description would be concerned with individual practice. The description is general, to give some illustration of the principles involved and a few of the common methods of practice. Carburizing is often looked upon as a necessary evil without much consideration of the possibilities of saving labor and cutting cost by the addition of mechanical equipment; in this field there is still much room for improvement, and in this direction a few suggestions have been offered.

CHAPTER IX

INSPECTION AND CONTROL

Objects of Inspection.—Inspection, like the keystone of an arch, so connects the results of the various processes and operations of manufacturing that the combination of these results will bear the burden of service. Inspection in manufacturing may be divided into three classes—inspection of raw material; inspection of the results of individual processes; and inspection of finished products and of finished assemblies. The manufacture of heat-treated steel products requires inspection of the raw material, of the results of processes or operations, and of the finished product, an inspection that is usually complete before the final assembly is made. Inspection of the raw steel requires analysis, or other tests for composition, and examination for condition. Inspection of the results of operations or processes may be carried on as a guide to the operator, to insure proper condition before the next operation—for example, if annealing is required before machining, or to show if specifications have been met.

Inspection for Composition.—The importance of composition has been discussed in other chapters; pointing out that the raw material—steel—includes a large number of alloys basically of iron and carbon but in which other elements, alloying elements, may be present and that the results obtained and the methods employed depend, to a large extent, upon the amount of carbon present and, also, upon the kind and amount of alloying elements that may have been added. Because of the effect of comparatively small variations in composition, narrow limits may be necessary, but even if comparatively wide limits can be allowed, the composition must at least be known. The composition of steel is determined by chemical analysis, although there are other methods by which a knowledge of composition can be obtained.

Inspection of steel for composition begins at the mill with the so-called "ladle analysis" of a sample taken from the heat

while molten and cast in a small ingot. The ladle analysis is often sufficient, because representative of the whole heat, provided that the entire heat goes to one user and is kept separate from other heats, thus simplifying inspection. Further inspection of the rolled product is usually necessary, however, because of variations that occur throughout the ingot and, also, because of the possibility of getting the wrong steel. Mixed stock and errors in shipping are common. The analysis of every bar in a shipment of steel will usually be too much of a burden, although sometimes the practice when close limits of composition are required. Representative samples from different portions of the shipment are usually taken. For this purpose, a small electric drill is a useful tool because easily carried to the lot to be sampled. Drillings must be clean and free from oil or other carbonaceous material that will appear as *carbon* when that element is determined by combustion. Chips for analysis are sometimes washed with naphtha or other similar solvents to remove any oil that may be present, and envelopes for the samples are usually not gummed as a further precaution. A small *rat-tail file*, magnetized, is convenient for picking up the sample chips. In some laboratories, milled chips are preferred to drillings, and pieces may be cut from bars for milling.

Marking Steel. Color Charts.—After being checked for composition, the raw steel is stored so that it can be drawn out as needed and must be marked so that the type can be distinguished. Such marking may be included in inspection. Painting the ends of bars in different colors according to type is standard practice, though forgings and other semifinished products are seldom marked but are stored in separate bins. For the color scheme, single colors or a combination of two colors are used, colors that are easily distinguished being selected. There is no universal color scheme because of the many types of steel only a few of which will be used in any one plant, and each user, therefore, selects his own scheme of which the following is a representative example.

Specimen Color Chart for Steel

S. A. E. 1015.....red	S. A. E. 3135.....red and white
S. A. E. 1120.....green	S. A. E. 2315.....blue and red
S. A. E. 1035.....white	S. A. E. 5150.....yellow and white
S. A. E. 1045.....yellow	Tool steel.....blue
S. A. E. 1335.....green and white	High-speed steel...red and green

Separation of Mixed Stock.—Analysis for composition, based upon representative samples, usually meets the requirements of production for inspection of composition and places no burden on the average laboratory and inspection department. If, however, two or more types of steel have been accidentally mixed, separation by analysis is a task too great and usually too expensive. Fortunately, there are tests by which such stock can be separated quickly and easily, tests sometimes as accurate as analysis. Of these the spark test is the easiest to apply and, perhaps, the most accurate in the hands of a skilled inspector. Anyone who has ground a tool or who has seen a tool ground is familiar with the bright-yellow spark thrown off from a tool of carbon steel and with the dull-red spark thrown off from high-speed steel, an easy method by which the two may be distinguished. The presence of chromium and nickel can be determined by the appearance of the spark, and different types of chromium or nickel steels can be distinguished as well. Unfortunately, these sparks cannot be reproduced in print, but they can be learned without difficulty by practice with steel of known composition.

Spark Test.—The spark test for carbon content is, perhaps, the most important because different grades of carbon steel are more easily mixed than other types. The spark test has been used for some time to separate steels having considerable difference in carbon content. The more the carbon content the brighter and longer will be the spark. Low-carbon steel has a very faint spark; high-carbon, a brilliant spark. A recent investigation of the carbon spark resulted in working out a method for determining carbon within a point or two by the spark test, practically as accurately as laboratory analysis. This is possible if the spark from a piece of steel of unknown carbon content is matched against the spark from steel of known analysis using a number of standards for comparison. Skilled operators learn to determine carbon closely even without standards. For this test a grinding wheel of medium grain and hardness traveling with a periphery speed of 4,000 to 5,000 ft. a minute is best, although other wheels and a somewhat lower speed may be used.

Dimethyl Glyoxime Test for Nickel.—Bar stock of different carbon content can also be separated by testing the electrical resistance of the bar, a method that has been fairly successful

although somewhat tedious. Nickel may be determined qualitatively by a simple chemical test with dimethyl glyoxime. The solution required contains;

1

Dimethyl glyoxime	1 g.
Acetic acid (80 per cent)	60 cc.
Ammonia (0.90 sp. gr.)	30 cc.
Ammonium acetate	10 g.

Dissolve and place in glass bottle.

2

Nitric acid 1:1 (1.20 sp. gr.)

Two medicine droppers and filter paper cut into small strips.

To make the test, clean the surface of the steel with a file, then wet with 1 drop of the nitric-acid solution. Let stand about 10 sec. and then absorb with filter paper. On this prepared surface put 2 drops of the dimethyl glyoxime solution. If the color changes to a strawberry pink, nickel is present; if it changes to a red brown, nickel is absent. The test is sensitive to about 0.18 per cent of nickel.

Inspection for Condition.—Chemical composition tells only part of the story, for condition is equally and often more important. Pipe, internal and surface seams, slag and dirt, lamination, and segregation, particularly of carbon, may have more effect upon the service of steel than composition. Some of these defects are plainly visible to the eye without any treatment to bring them out, but others become visible only after treating the steel, as by etching with acid. Examination for conditions that are easily visible is called "macroscopical." Some defects, on the other hand, can be detected only under the microscope, and examination for these is called "microscopical." To such tests may be added tests for physical properties if the raw material is to be formed or heat treated to obtain definite physical properties, for example tensile, hardness, and bending tests.

Macroscopical Examination. Deep Etching; Iodine Etching.—Macroscopical examination looks for pipe, surface seams and blow holes, segregation, and may include the observance of the effect of hot or cold forming by etching with acid to bring out the *flow lines*. Pipe, surface seams, and blowholes can be detected without etching. Such defects start with the ingot. No molten material solidifies all at once, and if a mixture, some separation of the constituents may occur. In the description of

(*a*) (*b*)

FIG. 62.—Sections of steel ingots.

the freezing of ice and salt solutions, in the first chapter, attention was called to the increase of salt in solution as ice separated out. In somewhat the same way, some of the constituents of steel segregate as the ingot cools. The top central portion is the last to solidify, and here a larger amount of carbon and some other constituents will be found. The ingot shrinks on solidifying, so that a cavity is formed at the top and continues for some distance into the center of the ingot, as shown in the photograph, Fig. 62 (*a*). When the ingot has been rolled, this portion is cut off and rejected. The depth to which the cavity penetrates is not always the same for each ingot, and, therefore, *cropping*

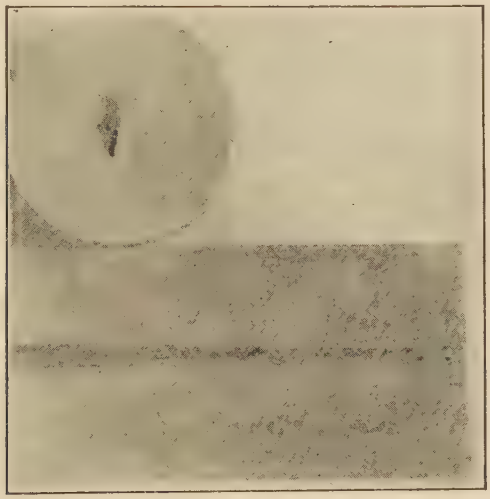


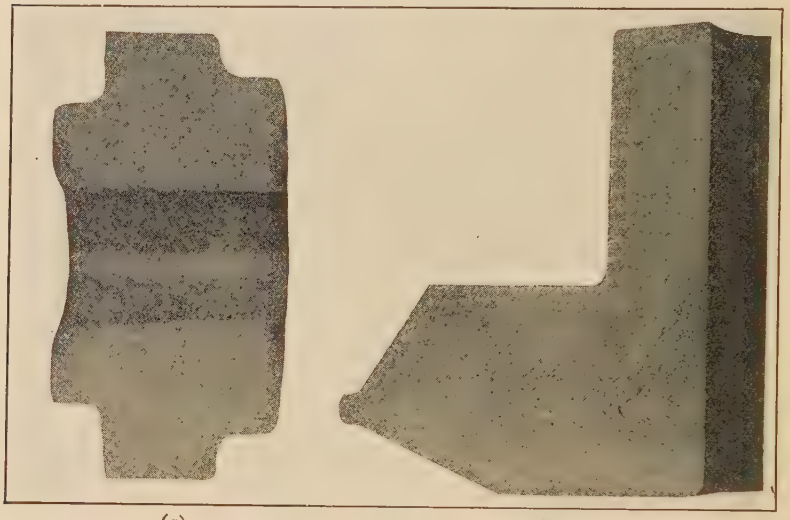
FIG. 63.—Pipe in rolled bar.

is sometimes insufficient. Steel containing this cavity is called "piped steel," which is easily detected by the eye. Pipe in rolled bar is shown in Fig. 63.

Ingots can be so cast that the top cavity will be small, but, as a result, blowholes will be formed at the surface, as illustrated in Fig. 62 (*b*). Such blowholes are often responsible for surface defects if not completely welded in the rolling and may appear as surface seams or slivers. Such defects are occasional rather than chronic, depending largely upon mill practice, but must be looked for particularly in sheet and wire.

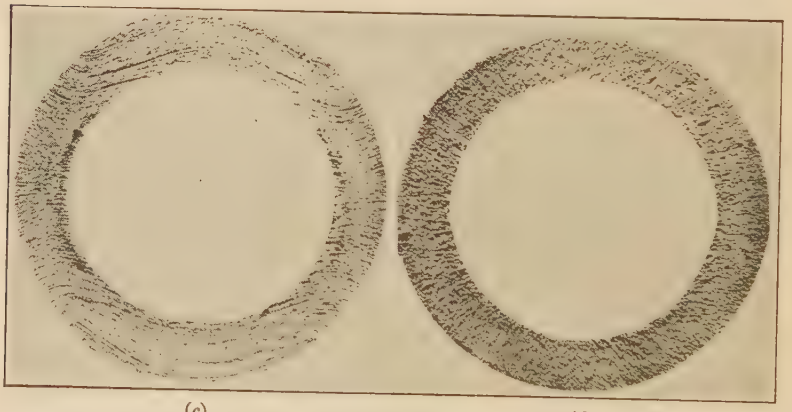
Lamination may be so pronounced that strips can be peeled from the surface but is more commonly a microscopical defect.

Segregation, on the other hand, is almost always observable to the unaided eye either in the fracture or by polishing and etching the surface. A common etching agent is hydrochloric



(*a*) (*b*)

FIG. 64.—Deep etch showing flow lines.



(*c*) (*d*)

FIG. 64 (*Continued*).—Deep etched ring gears.

acid, 1 part to 1 part of water. The test is made by cutting a section, usually through the center, polishing the surface, and covering with the acid solution for 24 hours or more, a method called "deep etching." Examples of deep etching are

shown in Fig. 64. Flow lines are clearly shown as in the two ring-gear forgings, one forged from a flat bar, the other made by upsetting a cylindrical bar. In the first, the flow lines are in one direction, across the face; in the second, lie at right angles to the face so that there is no *grain*. Surfaces to be deep etched to show flow lines should be smooth but do not need to be highly polished. On the other hand, segregation may be brought out in a shorter time, although, perhaps, to a more limited extent, by etching a polished surface with a solution of iodine, as in Fig. 65.

Macroscopical examination includes fracture tests for grain size and for depth of case in carburizing. Steel to be rolled or

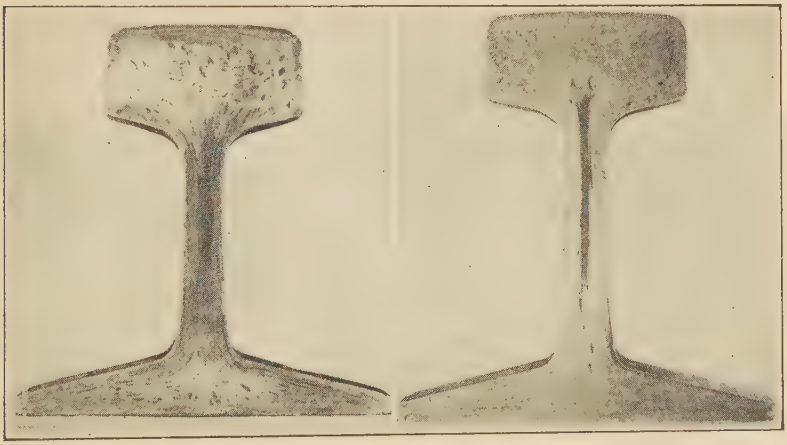


Fig. 65.—Iodine etch.

forged is heated to comparatively high temperature, and the grain size resulting is large but is reduced by mechanical work, The finishing temperature can be determined with fair accuracy by the appearance of the fracture. Burnt steel, steel so highly overheated that oxide of iron is formed at the boundaries of the crystals, is often detected more easily by the appearance of the fracture than by the microscope, particularly if heat treatment has followed the overheating. No heat treatment will restore burnt steel, but burning is often difficult to detect after treatment unless the fracture is examined.

Microscopical Examination. Non-metallic Inclusions. Structure.—The microscope will detect undissolved oxides, slag, and other non-metallic inclusions, commonly called "dirt," best

seen in unetched but polished surfaces. The oxide of iron formed in burning may be detected if burning has been severe, as in Fig. 66. Segregation and banding, sometimes called "lamination," is brought out by etching (Fig. 67). This is normal in some steels, particularly in some low-alloy steels, and does not necessarily indicate a defect, although such steel can give trouble in pressing. Banding follows from the ingot

FIG. 66.—Burnt steel. 100 diameters.

and is usually present to some extent, especially as ferrite bands. To such bands considerable attention has been given, and service failures have been ascribed to them, frequently in error. The ferrite bands shown in Fig. 68 were held responsible for failure of a part in ordinary service, but, in reality, failure was due to poor design. Ferrite bands of considerable size, however, have been responsible for service troubles. These

bands are usually accompanied by small particles of manganese sulphide, light grey in color, and manganese silicate, dark grey

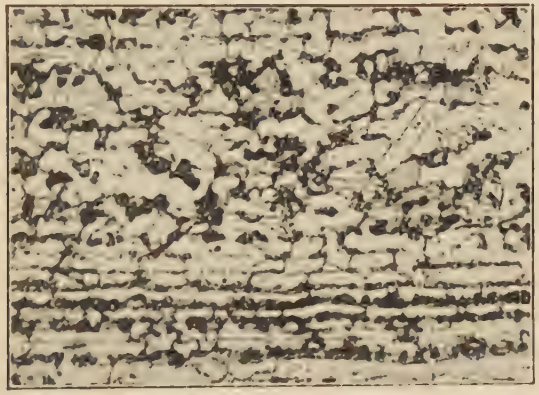


FIG. 67.—Laminated steel. 100 diameters.

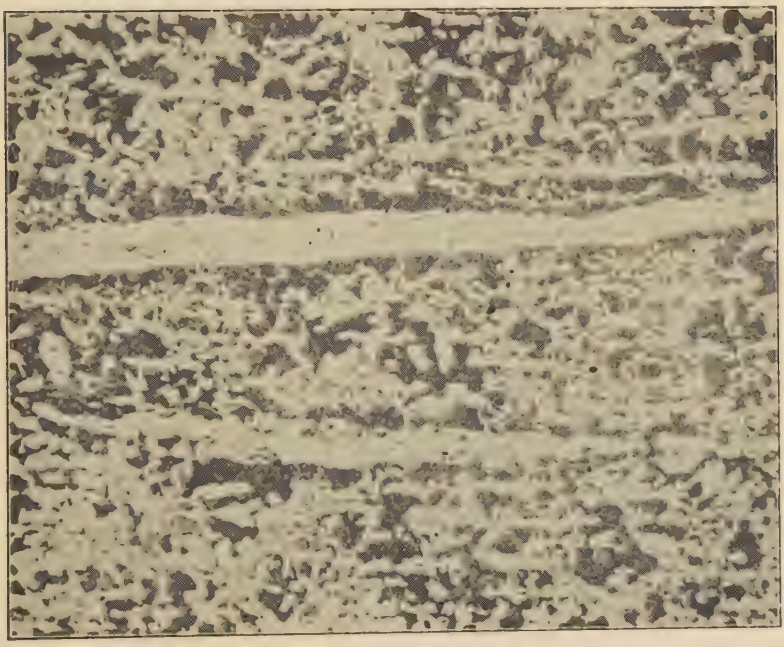


FIG. 68.—Ghost lines.

in color. The sulphide occurs in small globules; the silicate, in streaks, broken in rolling. Both are illustrated in Fig. 69.

The microscope is also used to determine the amount of dirt, oxides, slag, and other non-metallic inclusions. The effect of dirt in steel has been extensively discussed, usually with emphasis upon having no dirt at all. But even under the best conditions, non-metallic inclusions will be present. The amount of dirt that can be permitted depends upon the service required of the steel, and for much service a considerable quantity of dirt can be permitted. Manganese sulphide and other inclusions improve machinability and are not necessarily harmful. Much depends upon the size and shape of the particles. Tiny globules scattered uniformly can do little harm, but inclusions in streaks may cause trouble. For important parts, too much dirt is unde-

FIG. 69.—Manganese sulphide and manganese silicate inclusions. 100 diameters.

sirable, but the complete removal of inclusions from steel is impossible and unnecessary. Some will always be present. Inspection must draw a line of acceptance and rejection for kind and quantity. A satisfactory standard that provides facts rather than argument is illustrated in Fig. 70 (*a*), a series of photomicrographs of inclusions that is arranged in order of increasing amount and on which is indicated the maximum amount allowable for the particular service for which the steel is to be used. Steel containing more than this amount can be rejected. In practice such a series would include more examples, and rejection would depend upon the general condition rather than upon a definite comparison. A similar series for included oxides is shown in Fig. 70 (*b*).

The microscope is also a check upon the results of heat treatment, which can be determined by the structure as described in other chapters. If, for example, steel is to be heat treated before receipt, microscopical examination can check or replace

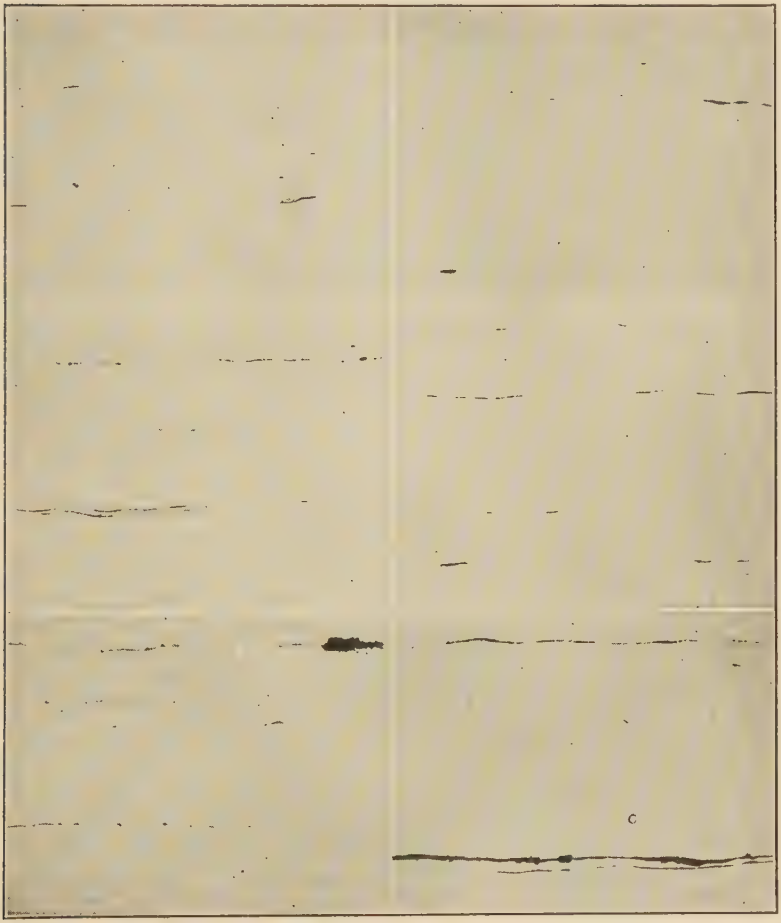


FIG. 70.—(*a*) Non-metallic inclusions reference series. 100 diameters.

tests for physical properties. Quenched steel contains no pearlite; its presence proves that the treatment has not been carried on or has been faulty. Inspection that is expensive and, also, destroys the usefulness of material is obviously not applicable to all material received. Macroscopical and microscopical inspec-

tion are, therefore, employed only as a general check upon condition. Routine inspection may include the examination of a few samples from each lot, a method usually satisfactory because the raw material is made in large batches.

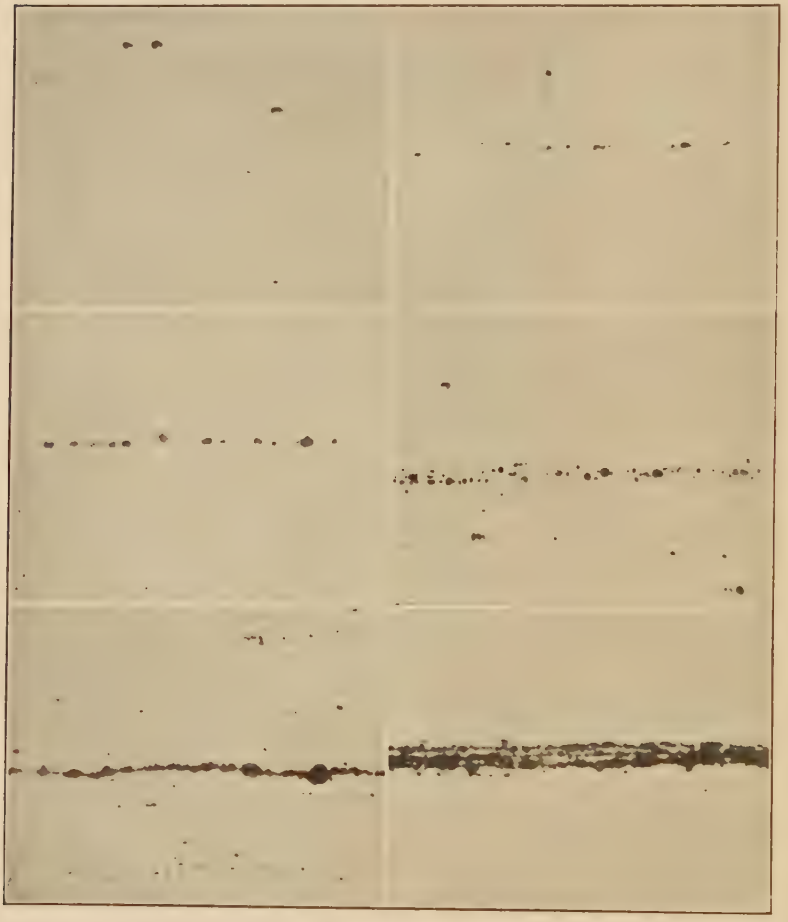


FIG. 70 (*Continued*).—(*b*) Oxide inclusions reference series. 100 diameters.

Hardness Testing. The inspection of finished heat-treated parts is based upon the object of such treatment to obtain definite physical properties, usually a certain degree of hardness. The method of inspection will depend upon the properties specified and, also, upon the size and shape of the piece. The tensile tests once the standard have been replaced by hardness

tests that can be applied to parts without destroying their usefulness. The tensile tests, however, check the hardness tests. Fracture tests and microscopical examination may be required to supplement such tests—for example, as a check upon heating or to determine the depth of case or to determine the conditions that result from the treatment. Such tests are not of so much importance as they were when scientific methods were first introduced. Modern manufacturing is based upon definite control to obtain the results required rather than upon inspection to detect errors. But because irregular results can occur in hardening in spite of such control, inspection for hardness may be applied to the entire output.

File Test.—When maximum hardness is desired, the method of testing may be simple, for example the file test, and the specification for such hardness is often only the phrase *file hard.* The file is useful for testing surface hardness in places such as the faces of gear teeth inaccessible to other testing devices. Soft spots are quickly and easily detected by the file. The cutting edge of a file is soon dulled, and tests with a dull file are of small account. A new cutting edge can be obtained by breaking off pieces as necessary. The file test can be used for *glass-hard* surfaces only. Steel that is moderately hard must be tested in some other way.

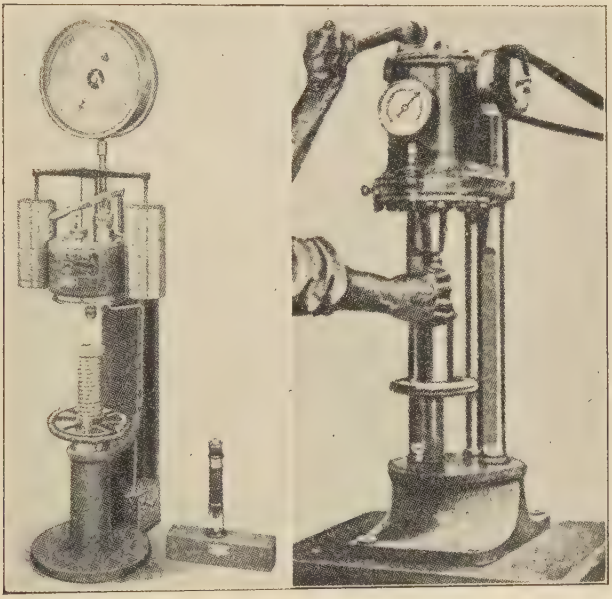
Standard Hardness Tests.—Tensile, or the equivalent torsional, tests remain the engineering standard but for production inspection have been replaced by a number of tests for hardness that do not require the spoiling of the piece for service. For a number of years, two such tests were standard, the Brinell and the scleroscope or Shore test. To these has been recently added the Rockwell test, and others have been developed. No one of these tests is suitable for all classes of work. Some are best adapted to testing for high degrees of hardness; others, a moderate degree of hardness. Some are suitable for small, finished parts; others for large, unfinished pieces. Some are adapted to testing thin pieces; but others can be used only if the piece is fairly thick.

Brinell Hardness Test. Description and Application.—Of these tests the Brinell is, perhaps, the general standard because adapted to the great bulk of heat-treated parts and because of long usage. Brinell hardness is based upon the size of the impression made by a hardened ball 10 mm. (about $\frac{3}{8}$ in.) in diameter. This ball is pressed into the surface of the piece to be tested with

Brinell-hardness Numbers
Diameter of Steel Ball 10 Mm.

Diameter of ball impression, millimeters	Hardness number for a load of		Diameter of ball impression, millimeters	Hardness number for a load of		Diameter of ball impression, millimeters	Hardness number for a load of		Diameter of ball impression, millimeters	Hardness number for a load of		Diameter of ball impression, millimeters	Hardness number for a load of	
	500 kg.	3,000 kg.		500 kg.	3,000 kg.		500 kg.	3,000 kg.		500 kg.	3,000 kg.		500 kg.	3,000 kg.
2.00	158	945	3.00	69.1	415	4.00	38.1	229	5.00	23.8	143	6.00	15.9	95.5
2.05	150	899	3.05	66.8	401	4.05	37.1	223	5.05	23.3	140	6.05	15.6	93.7
2.10	143	856	3.10	64.6	388	4.10	36.2	217	5.10	22.8	137	6.10	15.3	92.0
2.15	136	817	3.15	62.5	375	4.15	35.3	212	5.15	22.3	134	6.15	15.1	90.3
2.20	130	780	3.20	60.5	363	4.20	34.4	207	5.20	21.8	131	6.20	14.8	88.7
2.25	124	745	3.25	58.6	352	4.25	33.6	201	5.25	21.4	128	6.25	14.5	87.1
2.30	119	712	3.30	56.8	341	4.30	32.8	197	5.30	20.9	126	6.30	14.2	85.5
2.35	114	682	3.35	55.1	331	4.35	32.0	192	5.35	20.5	123	6.35	14.0	84.0
2.40	109	653	3.40	53.4	321	4.40	31.2	187	5.40	20.1	121	6.40	13.7	82.5
2.45	104	627	3.45	51.8	311	4.45	30.5	183	5.45	19.7	118	6.45	13.5	81.0
2.50	100	601	3.50	50.3	302	4.50	29.8	179	5.50	19.3	116	6.50	13.3	79.6
2.55	96.3	578	3.55	48.9	293	4.55	29.1	174	5.55	18.9	114	6.55	13.0	78.2
2.60	92.6	555	3.60	47.5	285	4.60	28.4	170	5.60	18.6	111	6.60	12.8	76.8
2.65	89.0	534	3.65	46.1	277	4.65	27.8	167	5.65	18.2	109	6.65	12.6	75.4
2.70	85.7	514	3.70	44.9	269	4.70	27.1	163	5.70	17.8	107	6.70	12.4	74.1
2.75	82.6	495	3.75	43.6	262	4.75	26.5	159	5.75	17.5	105	6.75	12.1	72.8
2.80	79.6	477	3.80	42.4	255	4.80	25.9	156	5.80	17.2	103	6.80	11.9	71.6
2.85	76.8	461	3.85	41.3	248	4.85	25.4	152	5.85	16.8	101	6.85	11.7	70.4
2.90	74.1	444	3.90	40.2	241	4.90	24.8	149	5.90	16.5	99.2	6.90	11.5	69.2
2.95	71.5	429	3.95	39.1	235	4.95	24.3	146	5.95	16.2	97.3	6.95	11.3	68.0

a pressure of 3,000 kg. (about 6,600 lb). For material softer than steel, the pressure is 500 kg. Devices for applying the load by means of a lever have been used, but the required load was obtained in the original machine by hydraulic pressure. To avoid overloading, this machine is equipped with a set of weights resting on a plunger that lifts when the desired load is reached. In some types, the weights are omitted, and two scales are provided on which the pressure is read directly, one being a check upon the



(*a*) (*b*)

FIG. 71.—Brinell machines. (*a*) Hand operated, (*b*) power operated (*Courtesy, Steel City Laboratories.*)

other. Figure 71 (*a*) illustrates a Brinell testing machine of the original type; Fig. 71 (*b*), a power-driven machine.

The relative hardness is determined by measurement of the diameter of the impression, usually with a small microscope equipped with a scale. The Brinell-hardness number that corresponds to the diameter in millimeters is taken from the chart shown. The relationship between the two is based upon a formula. Brinell hardness is sometimes quoted in millimeters rather than by the numbers.

In spite of the time required to make the reading, the Brinell test is rapid, particularly if a power-driven machine is used. When the Brinell method was first introduced, the pressure was continued for some time, averaging about ½ min., but this has been proved to be unnecessary. Error is possible, however, if the weights are lifted with a jerk and allowed to drop upon the holder with an increase in the size of the impression as a result. The additional operation, measuring the impression, is a disadvantage in comparison with direct reading, but this is not serious because other methods usually require more than one determination and the Brinell method but one. That the impression is permanent is an advantage. Direct-reading Brinell machines have been made but are not satisfactory.

The Brinell test is accurate for the average range of hardness obtained by heat treatment, up to 500 in terms of the Brinell scale, sometimes higher, but is not accurate for very hard steel because the impression will not always be round. The test cannot be applied to small or very thin pieces or to inaccesible places, gear teeth for example. Finished surfaces cannot be tested by the Brinell method if the impression will spoil the piece. The Brinell method is best applied to bars, rough forgings, or large tools such as die blocks.

Shore- or Scleroscope-hardness Test. Description and Applications.—The scleroscope or Shore test has been in service for some time, in many plants antedating the Brinell test. This test depends upon the height to which a small diamond-tipped hammer rebounds when dropped upon the surface to be tested, The rebound is measured by the eye, a scale being provided. or may be recorded on a dial. A glass tube is provided to control the falling hammer. Examples of this instrument are shown in Fig. 72. The scleroscope is usually placed on a swinging arm but may be removed for testing large pieces. A smooth, level surface is required, and a leveling rod is provided in the instrument to insure a vertical position.

The scleroscope is best adapted to testing hardened rather than comparatively soft pieces. In terms of its scale, from zero to approximately 110, the scleroscope is applied to testing in the hardness range between 45 and 110 and for some testing down to 35. The usual service is the testing of hardened and ground parts, particularly case-hardened parts that have been ground, as the instrument will detect a thin

case even if the surface is file hard. The scleroscope is a convenient instrument for testing large pieces, too large to place in a testing instrument or not easily moved, because it can be carried to the piece. Care must be used, however, in making such tests. Tests of thin pieces will not be satisfactory.

Because the principle is somewhat the same for both Brinell and scleroscope, the relationship between the two is fairly constant, although varying slightly with different types of

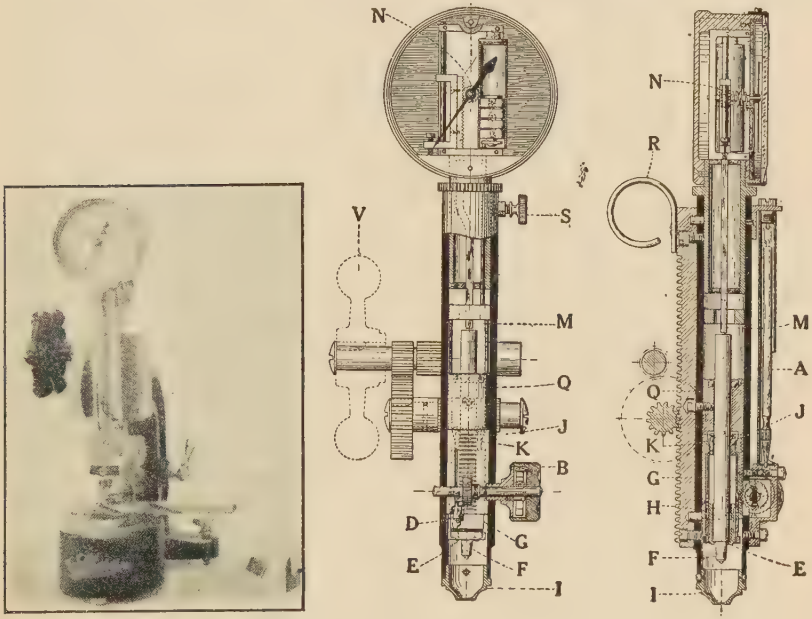


FIG. 72.—Recording scleroscope. (*Courtesy of Shore Instrument Co., Jamaica, New York.*)

steel. The ratio of Brinell to scleroscope hardness approximates 6.7 and 6.8:1.

Rockwell Hardness Test. Description and Applications.—The Rockwell-hardness test is a recent development and has been rapidly adopted for testing in a field not covered by either of the methods just described, particularly for determining the relative hardness of comparatively thin pieces, for example shovels. The instrument is illustrated in Fig. 73. After the application of an initial load, called the "minor load," a penetrator, a diamond cone, or a steel ball $\frac{1}{16}$ in. in diameter is forced deeper into the surface of the steel by a heavy load,

called the "major load," and the hardness is determined by the depth of penetration under the major load and indicated on a

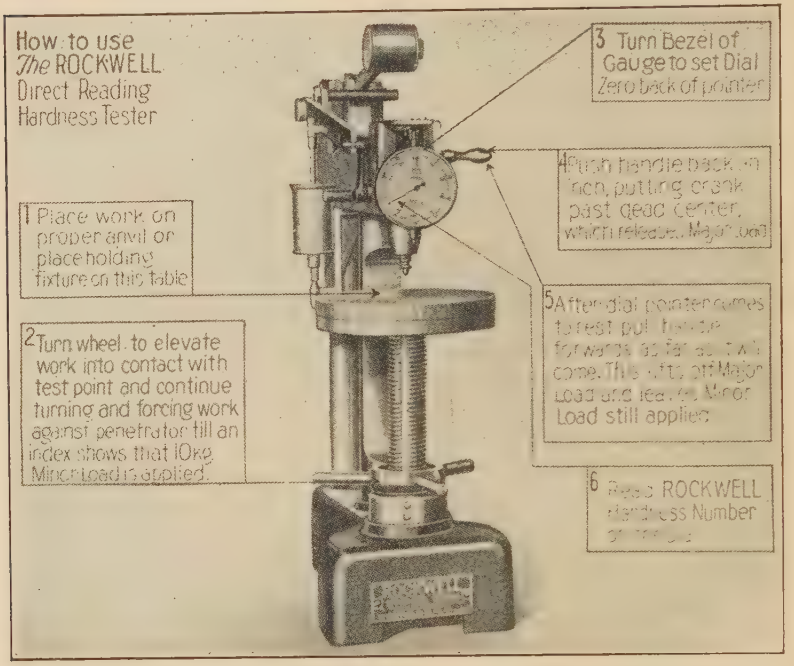

How to use
The ROCKWELL
Direct Reading
Hardness Tester
1 Place work on proper anvil or place holding fixture on this table
2 Turn wheel to elevate work into contact with test point and continue turning and forcing work against penetrator till an index shows that 10kg Minor Load is applied
3 Turn Bezel of Gauge to set Dial Zero back of pointer
4 Push handle back on arch, putting crank past dead center, which releases Major Load
5 After dial pointer comes to rest pull handle forwards as far as it will come. This lifts off Major Load and leaves on Minor Load still applied
6 Read ROCKWELL Hardness Number

Fig. 73.—Rockwell hardness tester. (*Courtesy Wilson Maculen Co.*)

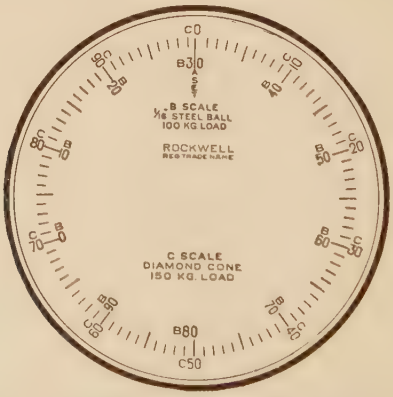


Fig. 73 (*Continued*).—(*a*) Rockwell hardness scale. (*Courtesy of Wilson Maculen Co.*)

dial, shown in Fig. 73 (*a*). The C scale is used for the diamond; the B scale, for the ball.

To make the test, the piece is placed on the anvil and brought into contact with the penetrator by the handwheel and screw, which is then turned farther until the pressure is brought to 10 kg., the minor load. The bezel of the dial is then turned until the pointer is set at zero. The major load is then applied, through a system of weights and levers, by turning the crank handle at the side backward, this returning on release to the original position. During the return, the pointer moves to the mark that indicates the Rockwell-hardness number. The major load is now removed, and the minor load is removed by turning the handwheel. The pointer continues to mark the hardness number until the minor load is removed.

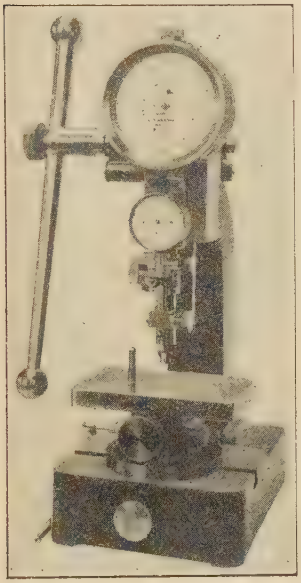


FIG. 74.—The monotron. (*Courtesy, The Shore Instrument & Mfg. Co.*)

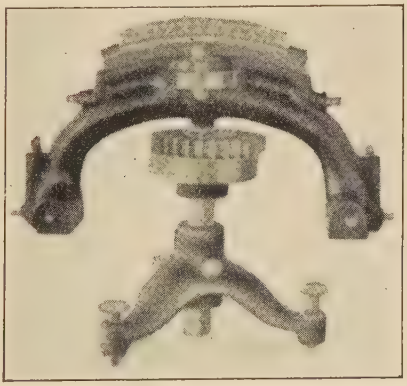


FIG. 75.—Herbert pendulum hardness tester. (*Courtesy of Tinius Olsen Co., Philadelphia.*)

The Monotron.—Another recently developed hardness tester, called the "monotron" and illustrated in Fig. 74, determines comparative hardness in kilograms pressure for a 0.36-mm. diameter impression made with a diamond ball point $\frac{5}{8}$ mm. in diameter. Two scales are provided, one for depth of penetration, the other for the load.

The Herbert Pendulum Hardness Tester.—Another device, illustrated in Fig. 75, the Herbert pendulum-hardness tester, consists of a pendulum weighing 4 kg. pivoted on a ball 1 mm. in diameter. The time in seconds required for ten swings is the time-hardness number. A scale over which travels a bubble of

air indicates the motion of the pendulum. A further test, *scale test,* is made by tilting the pendulum until the bubble stands at zero and then allowing the pendulum to swing. The position of the bubble on the scale at the end of the first swing gives the scale-hardness number. Inasmuch as no great pressure is exerted in applying the load, parts too thin for tests requiring pressure can be tested for hardness by this method.

Process Inspection.—Tests for condition and hardness are used for control of process as well as for final inspection, and heat-treatment processes require such inspection. For example, the proper drawing temperatures should be determined at regular intervals by tests for hardness. Even with close temperature control, the time required for carburizing should be checked by fracture test, samples being taken before the operation is presumed to be finished. The microscope is a valuable guide in checking depth of case, carbon content, and condition. Hardening temperatures can be checked by fracture test, a method invaluable in continuous furnace practice and in plants not equipped for complete control of pyrometers. Process inspection is often of more value than finished inspection, and the two are frequently combined. Process inspection, however, belongs to the heat-treating department rather than to the inspection department, because a guide to practice rather than inspection. Just as the machinist continually checks his results, so must the heat-treating operator control processes.

Specification. Forms.—Inspection and control of processes is necessary in practically all manufacturing, because the results depend upon definite changes in size, shape, or condition. The care required to control the results will depend upon the accuracy that is necessary and upon the ease with which the results can be determined. Some operations can be controlled by the appearance of the finished product or, perhaps, by a few rough measurements. Others must be controlled by careful measurement of, perhaps, great accuracy. Heat treating, unfortunately, seldom results in a change that can be observed from appearance or by simple measurement and, therefore, requires methods that will control these unseen results. Such properties as hardness or *spring temper* can be determined by a simple test, but the results usually required are by no means so simple. For accurate results, the requirements must be specified accurately. Close control is not possible unless the operator knows exactly what is

required. Manufacturing requires a definite statement of the object to be made and in advance of operations, a statement usually incorporated in a blueprint giving exact details.

The results required in machining operations have long been so specified, but heat-treating operations, because of a certain vagueness in the results, have only recently received the same attention. The blueprint might include such terms as "harden," "anneal," or "carburize," but the details were commonly left to the operator often because of the element of secrecy. Heat treatment, however, requires a statement of specifications just as definite as any other manufacturing operation, not only as a guide to inspection but also as a guide to the operator. Such specifications should include the desired composition of the steel, the physical properties required, the form in which the steel is to be treated, for example bar stock or forgings, the method of heat treatment, and the inspection required. Such specifications should be accompanied by reference to manufacturing processes that follow or precede heat treatment if one operation is dependent upon the other and should describe definitely the method of inspection. Such specifications should be flexible and provide for the salvage of material or finished parts that, perhaps, may not be within the limits specified. It is just as important to inspect for the purpose of saving material that will give good service as it is to reject material that will not be satisfactory. Specifications are often set for ease in manufacturing rather than for the results in service.

Specifications for heat treatment have often been added to the blueprint covering machining operations, a method that is satisfactory if the operation is simple. But such information can seldom be sufficiently complete, and its presence on the print complicates the making of changes. This is now generally recognized, and separate forms are provided of which an example is shown in Fig. 76, the actual size being $8\frac{1}{4}$ by $5\frac{1}{2}$ in., including margins. This form does not provide space for details, and all operations cannot be set down in regular order, so that it is somewhat inflexible. This difficulty is avoided by the form shown in Fig. 77, in which no spaces are provided for specific operations, only the general outline being printed on the form. The example illustrated shows how complete can be the information. To provide sufficient space, this form is usually of letter size $8\frac{1}{2}$ by 11 in. Both forms are used for blueprinting, the

lettering being made heavier by reversing a carbon paper on the back. Blueprints are distributed to the departments concerned.

In suggesting such forms, flexibility must again be emphasized. When the specifications do not go outside the plant, details may be closely described, but not too closely. For example, the drawing temperature and the hardness required should not be specified together. Better practice specifies hardness alone, perhaps suggesting the probable temperature. The composition of steel is none too closely controlled, and even with the same composition, results may vary from heat to heat for reasons still

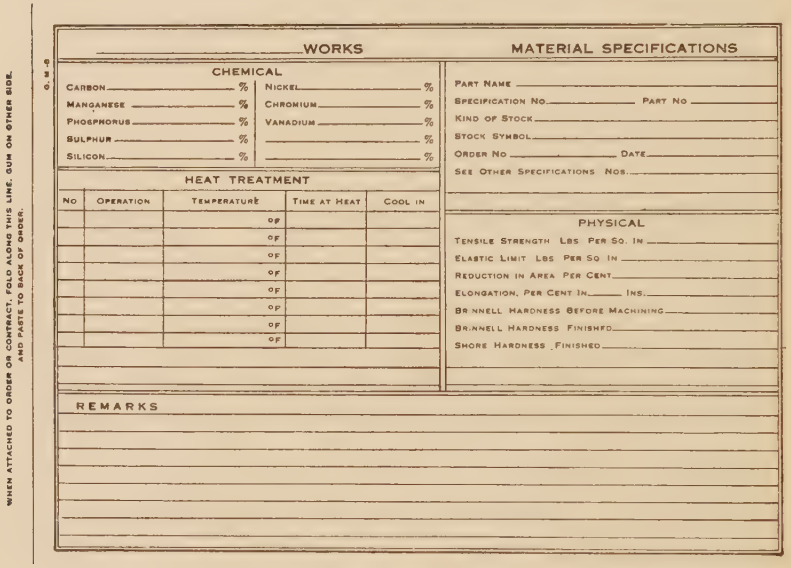


Fig. 76.

obscure. If specifications are sent to an outside maker, still more latitude must be allowed. The composition of the steel may be suggested or a preferred type specified, but specification should not include both composition and physical properties. If the heat treatment is to be performed outside, physical properties desired should be specified. If heat treatment is to be performed after the receipt of the parts, only the chemical composition should be specified. In all specifications, limits should be set in accordance with the ability to hold within those limits.

The control of heat-treating operations will be aided if a record of the operations and results is kept. Such records are

MATERIAL PART SHEET

Part Name	art No.
Camshaft—Motor	1000

Material Specification	Source
Steel S. A. E. 1015 Forging.	Purchase forging Heat treat and machine here

Chemical Analysis		Physical Properties
Carbon	0.10–0.20	File Hard before finish grind.
Manganese	0.30–0.50	Shore Hardness after grinding 70 minimum
Phosphorous	0.05 max.	
Sulphur	0.055 max.	Depth of case 0.045″–0.060″

Heat Treatment

1. Snag and clean surfaces to be copper plated.
2. Mill to length and straighten.
3. Rough turn bearings.
4. Copper Plate and wash thoroughly.
5. Straighten and finish turn bearings.
6. Rough turn cams.
[1]7. Carburize 1700° F. for depth of case specified.
8. Cool in boxes. Remove shafts.
9. Heat to 1425–1440° F.
[2]10. Quench in water.
11. Sand Blast.
[3]12. Inspect for hardness.
13. Straighten.
[4]14. Finish grind.
[5]15. Inspect for S. H.

Remarks

[1]Pack ends with clay. Pack test pieces in each carburizing box to check depth of case. Clay gear teeth.
[2]Use heavy flow of water and get shafts well down in tank.
[3]Inspect 100 per cent with sharp file.
[4]Use care in grinding to avoid surface checks.
[5]Inspect for S. H. 100 per cent
Analyze 1 per cent of forgings received.

Changes

Issued 1/3/29

Fig. 77.

valuable in determining cost but are, perhaps, of even greater value in determing methods of operation. Any variations from standard practice can be detected and the reasons for them can be more easily determined if a record is kept. In many plants such records begin with a blackboard ruled to provide spaces to record the time of charging and discharging, the temperature, the charge, and other items such as depth of case or the hardness. These records are copied from the board upon permanent forms.

Inspection for the Cause of Failure in Service.—The tests that have been described are also applied to steel that has failed in service in order to detect defects in the material. The composition may be wrong, the steel piped, burnt, or too dirty for good service; the case may be too deep or the hardness insufficient—these and other defects have been responsible for failure. There are, however, causes of failure, sometimes obscure, that are mechanical rather than metallurgical. Because the cause is often obscure and because defective material then becomes a convenient alibi, the condition of the steel has frequently been held responsible for breakage that, in reality, was due to a mechanical condition. An example of this was shown in Fig. 68, a picture of "ghost lines" that were held responsible for a failure that was due to mechanical conditions.

Unless failure can be very definitely shown to be due to defective material, inspection for the cause of failure should include an examination for faulty mechanical conditions such as nicks, sharp corners, overloading due to misalignment, for example gears improperly meshed, sections too small for the stresses applied, whip, and others that have been responsible for more failures than defective material. A gear tooth designed to carry a load evenly distributed will fail if the load is applied to only a small area. A shaft or bolt so placed that lateral movement is possible may fail because too small to resist the alternating stress. A shaft that whips will fail under a much smaller load than that for which it was designed.

Because of the "point" or "line" contact, ball- and roller-bearings sometimes fail in service because of heavy shock. Failure has been traced to improper methods of assembly particularly with ball-bearings that have been driven into place with a hammer rather than with a press. The effect of a blow can be illustrated by striking a hardened ball lightly

with a small hammer. If the ball is then placed in dilute nitric acid, the portion of the ball affected by the blow will spall off.

Much has been learned about design from a careful examination of parts that have failed in service because of faulty mechanical conditions, and inspection of parts that have failed should not neglect the possibility of such conditions or the fact that the cause is often obscure. Fracture will leave no trace of the nick or scratch that caused failure, and whip is not always easily detected. Continued failure of a particular part, particularly if breakage occurs in the same relative position, is nearly always a sign of a faulty mechanical condition. The occasional failure may give little concern, but inspection of parts that have failed should watch for conditions that may lead to a series of failures whether because of metallurgical or because of mechanical conditions.

CHAPTER X

FUELS

Fuels for Steel Treating.—The fuels that have been most commonly used for heat treating are coal, both anthracite and bituminous, coke, gas of different kinds, fuel oil, and to these electricity may be added. The selection of a fuel depends primarily upon comparative cost, actual cost, but availability of a fuel or adaptability to operating conditions may be more important than cost. Of these fuels coke and coal were the first that were available and are still used for heat treating, although to a small extent. Gas, oil, and electricity have replaced the solid fuels in spite of an apparently higher first cost, because the actual operating cost is lower or because they are better adapted to the service required.

Standards for Measuring Heat.—Each of these fuels has its own unit of measurement by which it is marketed, so that if a comparison of cost or service is wanted, some common ground is required. Comparisons are, therefore, based upon one feature held in common—heating power, the amount of heat obtained by combustion. The two units by which heat is measured are the Calory and the British thermal unit. The former, used in Europe and for scientific measurement, is the quantity of heat required to raise the temperature of 1 kg. of pure water from 15 to 16° C. The latter, the commercial unit of the British Empire and of the United States, is the quantity of heat required to raise the temperature of 1 lb. of pure water from 62 to 63° F., a unit commonly known as the "B. t. u."

Comparative Cost of Heat Units in Various Fuels.—A comparison of the cost of a number of fuels in terms of the available heat units is given in the following table, given for 1,000,000 B. t. u. The price of fuel varies continually, and for this reason an average price has been chosen and stated in round numbers for each fuel, so that calculation for higher or lower prices will be simple.

Fuel	Market price of	Cost of 1,000,000 B. t. u.
Bituminous coal (15,000 B. t. u. per pound)	$6.00 per ton	$0.20
Anthracite coal (13,500 B.t.u. per pound)	$12.00 per ton	$0.46
Coke (12,000 B.t.u. per pound)	$10.00 per ton	$0.42
Producer gas (150 B.t.u. per cubic foot)	$0.10 per 1,000 cu. ft.	$0.67
City gas (600 B.t.u. per cubic foot)	$0.60 per 1,000 cu. ft.	$1.00
Fuel oil (140,000 B.t.u. per gallon)	$0.05 per gallon	$0.35¾
Electricity (3,412 B.t.u. per kilowatt-hour)	$0.01 per kilowatt-hour	$2.93

Actual Cost of Fuels. Efficiency.—Such a table is useful for comparing the first cost of the different fuels but does not indicate comparative costs in service. The actual cost of a fuel depends upon other items also, for example the thermal efficiency of a fuel, the cost of installing and mantaining the equipment required, and the adaptability of the fuel to the purpose for which it is to be used. The efficiency of a fuel when burned is measured by heat actually used for productive purposes in heating the furnace charge, not that lost in the waste gases or by radiation or in other ways. There is no fixed standard by which the efficiency of fuels can be compared, because too many varying conditions enter, and equipment differs. From the commercial standpoint, a comparison that includes both fuel and equipment can be made by measuring the product turned out by a given quantity of fuel, either by weight, "so many pounds to the gallon of oil," or by the number of pieces. In this way, a comparison of fuels can be made, not only in terms of heat units but also in terms of dollars and cents. Heat units of low first cost may be very expensive if most of them are lost through the stack or by radiation.

First cost and efficiency together set a production cost that is directly chargeable to the fuel. There are, however, other items that affect the total production cost indirectly but which are also chargeable to the fuel. Such items as cost of installation and maintenance of equipment, rent of floor space, handling and transfer expense, and adaptability to the requirements of product or production may have more effect on the actual cost than the expense for fuel. Even a fuel that is low in price and high in efficiency may be at a disadvantage if much labor is required for its handling, if its use requires placing the department

at some distance from related production units, or if the cost of installing and maintaining equipment is high.

Other fuels of higher cost may be more suitable and actually cheaper. If the introduction of heat-treatment processes into other departments will permit operating at a lower expense, the fuel that will make this possible may be the most economical even if its first cost is high and its efficiency somewhat lower than that of other fuels.

Selecting a Fuel.—The effect of such items is so variable that each heat-treatment plant must be considered by itself. Under some conditions, a speeding up of production may more than pay for a higher fuel cost or a lower fuel efficiency; under other conditions, it may be more economical to produce at a slower rate. If, for example, it became necessary to increase production in a plant having only a limited space, a fuel that would make possible this increase without requiring additional space would be almost a necessity and might well be the most economical. Even if the cost of installing and maintaining the furnace equipment is high and the expense for fuel increased, a large saving might well be the result if the purchase and maintenance of additional land and buildings are prevented. On the other hand, when ample land or space in buildings is available, the demand for increased production can usually be met at a lower cost by increasing the equipment and using a lower-priced fuel.

Other items that are sometimes of importance in the selection of a fuel are uniformity of product, cleanliness, and freedom from distortion or change in dimensions. Certain fuels may meet such requirements more easily than others either because of their nature or because of the adaptability of the furnace equipment in which they are burned. Equipment is of as much importance as fuel, but fuel usually governs the equipment. Fuels that aid in producing results have little competition from a cost standpoint.

FUELS USED FOR HEAT TREATMENT

Solid Fuels. Advantages and Disadvantages.—Of the various fuels used for heat-treatment purposes coal and coke have seen the longest service, being the first fuels that were available. Although still used to some extent, solid fuels have been largely replaced by oil, gas, or electricity, fuels that can meet production requirements at lower cost or are better adapted to the conditions.

Economic conditions are largely responsible for the decreased use of solid fuels, but if these conditions change, such fuels may have a wider field, particularly if furnaces can be designed that will be efficient and that can also be heated uniformly throughout.

The advantages of solid fuels in heat treatment are:

Low cost of heat units.
Low cost of installation.
The independence of the individual unit with regard to fuel supply.

The disadvantage of solid fuel are:

Difficulty of handling
Low efficiency.
Intermittent heat supply due to the necessity for firing and cleaning at intervals.
Irregularity of temperature and uneven distribution of heat.
Variable rate of heating under natural draft due to varying weather conditions.
The length of time required to raise fuel and furnace to the temperature required.
Difficulty of close control.

Other advantages and disadvantages are concerned with the design of furnaces rather than with the fuel itself. For example, a furnace designed to increase the fuel efficiency would be advantageous, but if this design required too much floor space, the disadvantage might be greater than the advantage.

Some of the disadvantages of solid fuels are due to the handling methods that must be used and can be eliminated if the form of the fuel is changed to allow easier handling. The advantage of a change in form is shown by powdered coal, a fuel that has been used with success in a number of industries other than heat treating. Carried through pipe lines and introduced into the furnace through burners, powdered coal is more like liquid than solid fuels. It has been used very successfully in annealing malleable iron and in other processes somewhat similar to those of heat treatment. It is, however, not adapted to heat-treatment furnaces of conventional design, particularly because of the difficulty of removing the ash formed. Other fuels that meet the requirements to better advantage are available, so that powdered coal has not been given much consideration. It is possible, however, that some change in the situation may cause its introduction into heat-treatment plants.

Gas. Advantages and Disadvantages. City, Oil-process, Producer Gas.—In spite of the higher price, gas of various kinds has

replaced solid fuel in many heat-treatment installations. Natural gas was at one time extensively used but, except in a few localities, is no longer in service as a fuel for heat treatment or other industrial purposes. Its place has been taken by manufactured gas, producer gas, special-process gas, (usually made with oil), or city gas. The advantages of gas as a fuel for heat treatment are

Ease of control.
Simplicity and low cost of piping system.
High efficiency.
Ease of combustion.
Uniformity of heat distribution.

The disadvantages of gas are

High first cost.
Cost of installation and of equipment to make (this does not apply to city gas).
Low heating value by volume.

Of these disadvantages that of high cost may be balanced by efficiency, so that it can be used economically. The low heating value of city gas, however, is sometimes a distinct disadvantage. A large number of burners may be needed to supply the heat required, increasing the cost of piping. Special burners, however, are seldom required and a number may be controlled by one valve. If the pressure is low, it may be necessary to add a pressure booster to the line, a practice that sometimes means lowered pressure for other users and, therefore, may be opposed. Under average conditions, however, an ample supply of heat can be easily obtained without boosting.

City gas, when available, is a very satisfactory fuel, requiring no expensive equipment, and one that can be applied to a wide range of production. For these reasons, it is widely used, even in the face of a high cost, particularly in small installations. In a number of cities where manufacturing costs are low or where considerable quantity of coke-oven gas is available and can be added to the supply, city gas can often be furnished at a price that will permit of extensive use. Under present conditions, particularly in the treatment of large pieces, city gas is more expensive than fuel oil. It has been able to compete on account of availability or adaptability.

When city gas is not available or is high in price, either special-process, of which oil is the base, or producer gas can be used

when gaseous fuel is desirable. Oil gas has some advantages over producer gas in that its heating power is higher, and the cost of the equipment required for manufacturing is lower. When oil is cheap, special-process gas has a fair field in competition with other kinds. Producer gas has been more extensively used for heat treatment than oil gas but, although still used to a small extent, is no longer a fuel of importance. Its heating value is low, a disadvantage in comparison with other gases, although it can be increased by enriching. The expense for this is usually out of proportion to the results gained. The decline in the use of producer gas is due to the large amount of fuel oil available at a low cost and may not be permanent. It is, however, no longer a cheap fuel; coal has increased in price, and the cost of constructing and maintaining a producer plant is high. Fuels that do not require so much additional equipment will usually be preferred.

Producer gas is an excellent fuel for heat-treatment purposes. A highly oxidizing gas, its effect is to produce on the steel a thin coating of oxides that protects against heavy scaling. This "scale" loosens on removing the steel from the furnace, so that parts treated in a furnace heated by producer gas require little or no cleaning.

In manufacturing producer gas, the quality and quantity can be kept reasonably uniform, although some variation can be expected on account of the somewhat intermittent nature of the process. Some dependence must be placed upon the skill of the operator, and variations in quality and quantity may be noticed when shifts are changed. With a reasonable degree of skill the quality and quantity can be maintained within a range that will give perfectly uniform results at the furnace.

Fuel Oil. Types.—The fuel now used most extensively for heat treatment is "fuel oil," a term that covers quite a variety of products. Fuel oil may be a by-product in the refining of petroleum for which there is no commercial demand for purposes other than fuel, or it may be a crude oil too heavy to refine economically. The composition and properties of fuel oils vary considerably, sometimes because of differences of type, sometimes because changing market conditions increase or decrease the value of the various products derived by distilling or cracking crude oil. There are two general types of crude oil, one having a paraffin base, the other, an asphaltum base.

Properties of Fuel Oils. Specific Gravity, Viscosity, Flash Point.—Fuel oils are distinguished by certain properties of which specific gravity and viscosity are the most important. The handling and combustion of fuel oil depend on these properties, and light and heavy oils are carefully distinguished on the market. Tests for specific gravity are easily carried on, and specific gravity is, therefore, the usual commercial standard. If laboratory equipment is available, other properties may be determined. This may be necessary if large quantities of oil are obtained from widely different sources. Laboratory tests include determination of viscosity, the flash point, a pour test, and others of less importance.

Specific gravity is usually a very satisfactory standard by which to judge fuel oil if the supply is from few sources and is reasonably uniform. Fuel oils are usually classified by specific gravity, determined by hydrometer, the Baumé scale being commonly used. Division into three general groups is made including light, medium, and heavy oils. Using the Baumé scale, light oils, for example, may have a specific gravity of 28 to 32°; medium oils, from 22 to 28°; heavy oils, from 18 to 22°. Some fuel oils have specific gravities as low as 10 to 12° Bé., but such oils are seldom used for heat treatment.

Viscosity is, perhaps, the most accurate index of the ease with which fuel oil can be handled or burned. Viscosity is measured by the time required for a given quantity of oil to pass through a standard orifice at a standard temperature. A specification of viscosity might read, for example, "The viscosity at 100° F. shall not be greater than 100 sec." To this would be added the type of apparatus used for test, as *Saybolt Universal*, or some other similar device.

The pour test, by which is determined the lowest temperature at which the oil will flow, and the test for *flash-point* are of service in determining how fuel oil will behave when cold or when heated. The flash point is also a guide to the risks of handling and for safety is usually specified as "Not lower than 150° F."

On account of the many types of oils available for fuel, some knowledge of physical properties is necessary to provide for handling. Viscosity is, perhaps, the most important property, because an indication of the ease with which oil will flow. Specific gravity will usually give some idea of the viscosity because the

two are closely related. In terms of viscosity, fuel oils may be classified into four types: oils that can be easily handled under the usual range of operating conditions without preheating; oils that can be easily handled in warm weather but require moderate preheating in cold weather; oils that can be handled in warm weather without preheating or with a moderate amount but requiring preheating to a fairly high temperature in cold weather; and oils that must be preheated at all times. The first three types would be recognized by specifying, respectively, viscosities of "not over 100 sec. at 100° F. 8;" "not over 200 sec. at 100° F.;" "not over 300 sec. at 100° F." (Saybolt).

Preheating Fuel Oil.—Preheating is the method by which oils that do not flow well when cold can be made serviceable. Preheating temperatures must be kept below the flash point or else a large amount of light vapor will be formed that will make combustion difficult, much as if water were present in the oil. The usual preheating temperature is about 30° F. below the flash point. For the lighter oils, preheating temperatures lie between 100 and 140° F. (40 and 60° C.). For heavy oils, preheating temperatures may lie between 165 and 200° F. (75 and 95° C.). For the lower temperatures, exhaust steam can be used for heating; but for the higher temperatures, live steam will be necessary. If no laboratory equipment is available for testing, the specific gravity may be taken as a guide and preheating temperatures finally determined by trial. Underheating will be shown by the sluggish flow; overheating, by difficulty in combustion, already mentioned.

Advantages of Heavy Fuel Oil.—In spite of the greater ease of handling light oil, there are advantages in the use of heavy oils due to the lower cost and the larger number of heat units per unit of volume. Preheating will remove most of the difficulty in handling and may not be a disadvantage because even the light oils frequently require preheating in cold weather. Light oils are not always available, so that it is advisable to be prepared to handle heavy oil.

Fuel oils are not entirely liquid as some solid matter may be carried in suspension. This solid matter may settle and form a sludge at the bottom of the storage tank and often enters the fuel lines and clogs the burners. Water is also commonly present in fuel oil or may be introduced through leaks in the steam lines used for heating. Dirt and water can be responsible

for much trouble at the burners but can be controlled by various methods that will be described later.

Advantages and Disadvantages of Fuel Oil.—With this brief outline of the conditions which affect the use of fuel oil, its advantages and disadvantages in comparison with other fuels may be considered. The advantages are:

Low first cost.
High efficiency.
Concentration of heat units in small bulk.
Independence of supply, ease of storage.
Availability.

The disadvantages of fuel oil are

Difficulty of handling, requiring special equipment for storage, pumping, burning, and heating.
Variation in quality.
Presence of sludge, water, and other foreign materials causing difficulty in burning
Necessity for careful control at the burner, a minor disadvantage.

Most of the disadvantages of fuel oil may be overcome if proper equipment is provided and if the fuel-supply system is properly designed.

Equipment for Handling Fuel Oil.—Fuel oil requires equipment for storage, handling, and combustion. Sufficient storage capacity for an emergency supply over and above production requirements will be necessary, provision must be made for heating the oil, and the system must be equipped with pipe lines, pumps, pressure regulators, control and relief valves, burners, and other apparatus.

Storing Fuel Oil. Sludge.—Fuel oil is usually stored in tanks of boiler plate placed underground, this location being a legal requirement in most states. In some cases, however, since storage aboveground may not necessarily present a dangerous fire hazard, such location may be permitted, and installation made at less expense. The loss of heat may be greater than it would be if tanks are placed underground, but this objection is not serious. Measuring devices must be supplied that will tell quickly the amount in storage, such devices varying from simple float indicators to more complicated pressure gages. Where storage is above the ground level, only the simpler devices will be required.

Convenience in handling requires the location of storage tanks as near as possible to the heat-treatment department. If fuel oil is delivered in tank cars, tracks should be placed close to the tanks. In Fig. 78 is shown a convenient arrangement of a battery of storage tanks in connection with the heat-treatment building, with a track arranged for the handling of tank cars as well as for general purposes of receiving and shipping.

The handling of fuel oil in storage presents some problems that must be solved if perfect combustion at the burners is to be obtained. Water and solid matter—sludge—must be kept from the burner, and it also may be necessary to maintain the temper-

Fig. 78.—Fuel oil tanks.

ature of the oil to provide sufficient flow. Water is more or less easily removed from oil by settling and draining, but sludge presents another problem. In some plants, sludge is not allowed to form, the oil being agitated to prevent settling, and the solid matter is carried to the burner. Some oils carry too much solid matter for such treatment, and, furthermore, it is sometimes difficult to prevent clogging of the burners. Sludge is usually allowed to settle and is shoveled out from time to time.

Some chemicals, for example naphthalene, will liquefy sludge. A number of mixtures, of which naphthalene is the base, have been placed on the market. The price of such mixtures is much higher than that of naphthalene, which can be used very satis-

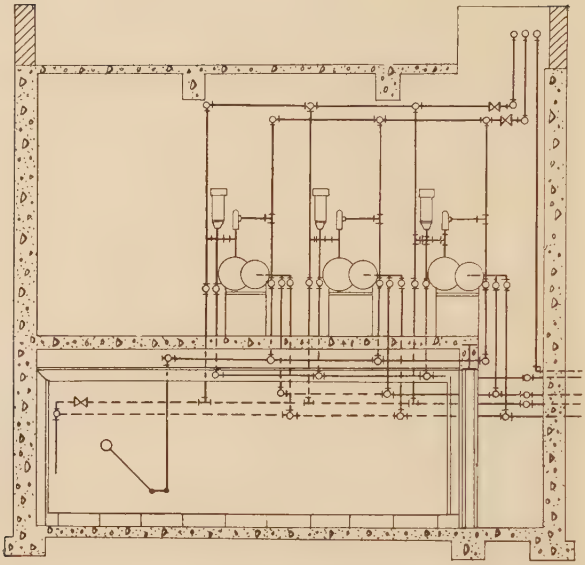


FIG. 79*a*.—Pumps and sump for fuel oil.

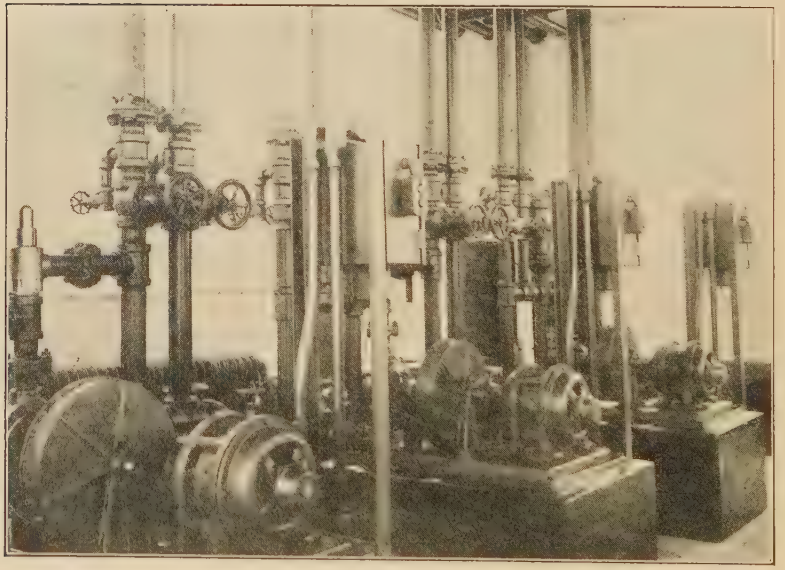


FIG. 79*b*.—Fuel oil pumps.

factorily. The addition of fuel oil to the sludge will help in liquefaction with chemicals. A small amount of kerosene can be added if the sludge is very heavy. Chemicals can be added to the oil to prevent (at least in part) the formation of sludge. One pound of naphthalene to from 400 to 800 gal. of oil is customary practice, the exact amount depending upon the condition of the oil. A larger amount is necessary to liquefy sludge.

If the sludge is allowed to settle to be removed later, oil should be pumped from the top of the tank and not from the bottom. A float for the intake is shown in Fig. 79*a*. Free movement of the intake pipe is obtained by the use of loose threads in the connecting elbow. Fuel oil may be drawn in this way directly from the storage tanks, but it is better practice to provide a sump, a secondary settling basin and tank, from which oil can be pumped directly to the burners, and which can be filled, in turn, from the storage tanks. In this way, cleaner oil will reach the burners, better temperature control of the oil is possible, and the pumps can be so located that the highest efficiency can be obtained. Figure 79*a* illustrates a fuel-oil system that includes such a sump.

Allowing the sludge to settle is one way by which cleaner oil reaches the burners, but the removal of sludge from the sump or tank is by no means simple, particularly if the sludge accumulates quickly. Some operators prefer to burn the sludge with the oil and may provide agitators to stir up sludge so that it will be carried to the burners with the oil, using special burners that will not clog easily if trouble is experienced with standard types of burner.

Pumps and Pipe Lines.—From the sump or storage tank fuel oil is delivered to the burners by pumps, usually under a pressure of 30 to 40 lb. These pumps are of various kinds, the two types most favored being the steam-driven and the motor-driven centrifugal. Figure 79*b* is a picture of the battery of motor-driven centrifugal pumps shown in the sketch in Fig. 79*a*. Of the three pumps shown, one is usually intended for the burner supply, another for unloading tank cars or for supplying the sump from the storage tanks, the third as a reserve for emergencies. In small plants, one pump is generally sufficient, but if heavy duty is required, a duplicate is desirable.

Storage tanks and pumps should be located as close as possible to the plant supplied, not only for convenience but also to avoid

cooling the oil. When trenches are used, the pipe lines can be protected and parallel steam lines added to keep the oil up to the temperature desired. Steam lines may be a necessity if the oil travels a long distance. A considerable number of plants have the storage tanks located a long distance from the furnaces, the oil passing through supply lines buried in the ground only a short distance below the surface. These conditions have been responsible for much trouble in handling fuel oil.

The arrangement of the piping system is also important in its effect upon the condition of the oil when delivered at the burner. Oil-supply lines should always be connected with a return line so that the unused oil can be carried back to the sump or storage tank, a pressure-relief valve being located at the junction. Dead ends should always be avoided in pipe lines for fuel oil. Under the best conditions, oil will cool when pumped into cold pipes, but if a return line is added, the cold oil may be carried back to the tank and warm oil continually circulated until the pipes are thoroughly heated. The temperature of the oil can be kept nearly constant, and the pressure will be more uniform.

Uniform pressure is necessary for satisfactory combustion of fuel oil, and if this cannot be maintained by the pump, a pressure regulator will be necessary, adding a pressure-relief valve in the line. To obtain uniform pressure without the use of pressure regulators, fuel oil is sometimes pumped to a tank placed well above the level of the burners to which the oil flows by gravity. This method does not represent common practice, being too cumbersome for plants using large quantities of fuel oil, and is not necessary when satisfactory pumping equipment can be secured at a low price.

Methods for removing solid matter and water from fuel oil have been considered in another paragraph in connection with storage and delivery to the pumps. To ensure the removal of all solid particles as far as possible, strainers are often placed in the pipe lines passing to the burners, a method mentioned here on account of its connection with the pumping system. Such strainers are usually wire cloth of fine mesh located at the end of the intake pipe, small strainers being sometimes included in the burner. As a general rule, it is better practice to avoid the use of strainers as much as possible, particularly if the oil carries a considerable quantity of solid matter in suspension. But if strainers are required, they should be

easily accesible for cleaning. Strainers should be cleaned at regular intervals, otherwise the oil supply may be shut off by the accumulated dirt.

Air Supply for Combustion. Blowers. Steam Induction.—The combustion of fuel oil in furnaces requires a supply of air either delivered directly to the burner under pressure or induced. To supply this air directly, a blower is necessary and is an important part of the system. The choice of a blower deserves careful consideration, for much trouble will follow if the wrong selection has been made. The amount of air required should be carefully estimated and an allowance made above this amount. It is safer to have more air available than actually needed. The pressure under which the air is delivered is also important. Blowers are built to deliver at pressures varying from about 8 oz. up to 2 or 2½ lb. For heat-treatment purposes, 1½ to 2 lb. should be used. Blowers in service vary all the way from the individual blower attached to each burner and operated by a motor to large motor-driven centrifugal blowers supplying all the burners. One type of centrifugal blower has been very successfully operated in both small and large plants, one that is direct connected with an induction motor and, therefore, uses power only in proportion to the air drawn off.

Air compressors have been used to some extent in heat-treatment plants but are now generally replaced by the centrifugal blower. Air under very high pressure is not necessary for the combustion of oil, although valuable when gas is used. The cost of operating an air compressor is high, more space is required than is necessary for the centrifugal blower, and it is also more expensive to buy and maintain.

Air may be delivered to the oil by induction, using steam. This method is simpler than delivering the air directly, no special apparatus being required if steam is available. Steam not only supplies air by induction but also heats and atomizes the oil. The amount required is comparatively small, hardly noticeable in a large steam consumption for other purposes. Steam has some disadvantages if very high furnace temperatures are required but is satisfactory when furnace temperatures range from 900 to 1800° F. (480 to 980° C.), the customary range in most heat-treatment operations. It is economical only if also required in the plant for other purposes. Forge shops, for example, may require steam for hammers, and steam

engines may supply power. If steam is not so available, air can be supplied more economically by blowers.

Preheating Air.—Air for combustion may be preheated, utilizing the waste heat from the furnaces, by placing the air lines in the roof or walls of furnaces or in the outlet flues or by means of a separate chamber for heat transfer placed above or below the furnace and containing separate passages for flue gases and air. Theoretically, preheating the air should lower the oil consumption, but practically, it is not economical unless the temperature is raised to 700° F. (370° C.) or more. Air heated to lower temperatures will help to lower the viscosity of the oil at the burner so that if the oil must travel a long distance through cold pipes, preheating the air may be of service in obtaining clean combustion. Good practice avoids such makeshifts, however, equipping to maintain proper oil temperatures throughout the system. Temperatures necessary for economical results can seldom be obtained in average heat-treatment practice, particularly when the operation calls for maintaining a uniform temperature for long periods of time, as in carburizing. Special furnaces that lose much heat in the waste gases, for example lead pots, may often be equipped economically with preheaters for air, because high temperatures can be obtained. On the other hand, the amount of heat in the waste gases is usually so high that greater economy will be obtained if used to heat another furnace of smaller size or to heat another furnace that is maintained at a lower temperature than the one from which the waste gases are obtained.

Burners.—The vital part of the equipment for the industrial combustion of fuel oil is the burner, because liquid fuel is so concentrated that it must be supplied in comparatively small quantities under close control. Perfect combustion requires that the liquid be broken up as much as possible into small particles and that these particles be in immediate contact with the air necessary for combustion. The aim is to approximate gas as nearly as possible. Specially designed burners are necessary to make the proper combination of oil and air and to control the quantity of oil supplied.

In its simplest form, an oil burner can be described as a tube reduced in size at one end to provide a small orifice by which the amount of oil passing is regulated. This regulation may be obtained by making the orifice of definite size or by varying the

size of the orifice as desired, the latter method being more generally used. To the burner fittings are attached for connecting the oil and air (or steam) lines, these being equipped with the valves necessary for control.

The simplest form of standard burner for oil is the needle valve in which the size of the orifice is controlled by a "needle," a rod ground to a point so that it will fit the orifice. A screw thread and handle are provided by which the point can be moved in and out of the orifice, permitting control of the flow of oil. A typical needle-valve burner is shown in the photograph, Fig. 91. The auxiliary air line placed just below the burner should be noted, this supplying additional air for increased combustion. The needle-valve burner is inexpensive and easily regulated, but it is not easily forced, and for this reason the addition of an auxiliary air line is advisable. The flow of oil through the outlet will be stopped by small, solid particles, a disadvantage that has led to other designs. In one such design, the pointed needle is replaced by a larger rod ground at the end to a frustum of a cone, with a correspondingly larger orifice. In another design, the oil passes through a slot over which is placed a movable lip for regulating. The larger area provides more than one point or outlet for the oil, so that small, solid particles will not interfere with the flow of oil so easily as in the needle-valve burner. Complete descriptions of burners can be found in trade journals, in the manufacturers' catalogues, or in textbooks.

Automatic-burner Regulation.—Until recently, the control of burners required the attention of a skilled operator, but with improved furnace design that permitted uniform heating, automatic-burner regulation under pyrometer control has become possible, and apparatus for this purpose has been placed on the market. Although methods of control vary, there are two general schemes by which such control is obtained. With one method, the burner is adjusted to permit the passage of the maximum or nearly the maximum amount of oil and is opened or closed completely as the temperature falls below or rises above the point desired. With the other method, the flow of oil is controlled and can be varied by regular steps in much the same way that it is controlled by hand. The first method, known as "on and off," is generally preferred because simpler. Automatic temperature control will be described in more detail in the chapter on temperature control.

The advantages of automatic control are in the elimination of the human element, although an operator will be required to regulate the burners from time to time if the temperatures employed vary and, also, possibly, at the start; in lowering labor cost; and, sometimes, in lowering fuel consumption. On the other hand, if skilled labor that can be used to operate furnaces is required for other purposes, automatic control may have no advantage. A skilled operator can control a number of furnaces almost as closely as is possible with automatic control. The cost of automatic equipment is high and may represent only an unnecessary expense. From the operating standpoint, automatic control is usually advantageous for processes that require the maintenance of uniform temperature for long periods of time. Such processes are carburizing, the treatment of a large number of heavy parts, and long-time annealing. When there is a constant rise and fall of temperature within short-time intervals, or if operating temperatures are constantly being changed, automatic control may be disadvantageous.

ELECTRICITY

Advantages and Disadvantages. Comparison of Cost.—Electric furnaces for heat treatment have been in use for some time principally for tool hardening or for the treatment of small parts in small lots. It is only recently that electricity has been used for quantity production in heat-treatment plants. Cheaper current and improvements in furnace design, which made possible a high efficiency and uniformity of temperature, have been responsible for the rapidly increasing use of electricity for heat treatment. For this purpose, electricity approaches the ideal source of heat. Its advantages are:

High efficiency.
Cleanness as a fuel.
Cleanness of work treated.
Easily and closely controlled.

The disadvantages of electricity for heat-treatment purposes, principally economic, are:

Cost of current.
Cost of equipment, including transformers and furnaces.

Electricity is a high-priced fuel, but, nevertheless, electric furnaces are coming into extensive use, and a number of large

plants are treating steel entirely or almost entirely with such furnaces.

Electricity at about 1 ct. per kilowatt-hour can compete with oil at 8cts. per gallon partly because of the greater thermal efficiency obtainable with electric furnaces and partly because of a saving in the cost of handling. A comparison between the actual cost of electricity and that of other fuels is difficult because of the number of factors that enter. Care must be taken, furthermore, not to compare efficient furnaces for one fuel with inefficient furnaces for another fuel. Conditions differ in different plants, particularly with regard to the product, and cost varies with different products. A comparison of the cost of oil and electricity for heat treating one product will be given. This comparison is based upon efficient furnaces for each fuel.

Electricity	Fuel Oil
General Average Heat to 1550° F.	
10 lb. per kilowatt-hour	220 lb. per gallon
Long Runs	
11 lb. per kilowatt-hour	240 lb. per gallon

Comparative cost per pound will be

Electricity at 1 ct. per kilowatt-hour	0.1 ct. per pound
Fuel oil at 7 cts. per gallon	0.032 ct. per pound

Comparative figures for drawing at 1050 to 1100° F. on general average are:

Electricity	Fuel Oil
17.5 lb. per kilowatt hour	285 lb. per gallon

Another source reports 200 lb. per gallon of oil in heating one product to 1550° F. On drawing at 900° F., 625 lb. are heated with 1 gal. of oil. Carburizing at 1700° F. for $\frac{1}{16}$-in. case required 1 gal. of oil for 120 lb. with a recuperator and 105 lb. without the recuperator.

For hardening at 1425° F. with oil, fuel figures vary from 100 to 200 lb. per gallon of oil.

Figures on another large installation of electric furnaces are

Degrees Fahrenheit	Pounds per Kilowatt-hour
Heat to 1650	10
Draw at 1250	17.6
Heat to 1000	26
Carburize for $\frac{1}{16}$-in. case	17.6

(Carburizing is carried on in a counterflow furnace in which two lines move in opposite directions, the incoming charge being heated by the outgoing charge.)

According to these figures, the cost of heating with electricity is about three times the cost of heating with oil for the hardening and drawing operations. For carburizing, the cost is about the same, although the electric furnace has the advantage in being recuperative. These figures are based upon electricity at 1 ct. per kilowatt-hour and oil at 7 cts. per gallon. The additional cost of heating by electricity in hardening and drawing operations would be prohibitive if it could not be compensated for in other ways. The electric furnace is preferred for careful treatment because of the close control of temperature that is possible and because of the cleanliness of the product. It may be possible, however, to produce equally good conditions with fuels of lower price by attention to furnace design. The electric furnace can be designed so that there will be no surplus material to be heated. But to compete with fuel of lower cost, continuous running is required. Heating up the electric furnace, particularly a large furnace, is costly, and more so if there is a maximum demand charge.

Possibilities of the Various Fuels.—At the present time, oil, because of its comparatively low price, is used to a much greater extent than other fuels. The cost of electricity is frequently too high, and installations that have been made because of the greater efficiency have often been found to increase cost to a considerable degree. Gas is still a high-priced fuel, particularly city gas, but is used in many plants because of the greater ease of operating, because cleaner than oil, and because no equipment for handling is required. It is a very satisfactory fuel and should become cheaper, although some radical changes in the methods of manufacturing will be required. Gas is applied more to hardening, particularly tool hardening, and oil, to the heat treatment of forgings as well as to hardening. Both fuels have an advantage over electricity in that they permit forcing, rapid heating. Forcing the electric furnace is limited because of the danger of burning out the heating elements. Conditions of cost and application change so rapidly with the various fuels that neglected fuel of today is the preferred fuel of tomorrow.

CHAPTER XI

FURNACES FOR STEEL TREATING

STATIONARY-HEARTH FURNACES

Classification of Furnaces for Heat Treating.—Furnaces for heat treating differ so in construction and in purpose that description can follow several different plans. Such furnaces may be classified according to the fuel required, for example as coal-fired, oil-fired, gas-fired, or electric furnaces; according to the method of applying and distributing heat, using descriptive expressions such as "overfired," "underfired," "muffle," "semi-muffle;" according to the process to which they may be applied, of which carburizing, hardening, annealing, cyaniding are examples; or by the construction, a classification that includes such terms as "stationary," "pot," "rotary," "continuous," and others of a similar nature. A full description of a furnace requires reference to all of the features that affect the design. The term "coal fired," for example, describes the fuel rather than the furnace, but a furnace described as a semimuffle stationary, underfired, oil-heated hardening furnace is almost completely pictured.

Furnaces are seldom described in such detail, because brevity is desirable. But because there are so many salient features, no general classification, upon which a discussion of furnaces can be based fully, is possible. Modern industrial furnaces, however, are the result of a series of steps that begin with an uncovered bed of solid fuel and extend to the comparatively complex construction of the present. The introduction of fuels more easily handled and controlled than solid fuels, such as charcoal and coal, has been responsible for better furnace practice, but progress has also been due to improvement in furnace design that followed a demand for rapid, economical, and uniform production, and, in time, principles of design have been established. Some of the principles may apply to the design of all or nearly all types of furnace, but many of the

details of construction will depend upon the kind of fuel used. For example, an oil-fired and a gas-fired furnace may be alike in general construction, but the combustion chamber and flues will be larger in the oil-fired furnace, other conditions being alike.

Principles of Furnace Design.—Practice has changed from one fuel to another in somewhat regular steps; from solid fuel to gas and oil and from gas and oil to electricity. Such changes do not mean that one fuel has been abandoned for another; they mean that additional fuels have become available. With the addition of a new fuel has followed the development of furnaces suitable for that fuel, furnaces that can be heated economically and uniformly. Because of the importance of fuel in connection with furnace construction, furnaces can be, and will be here, discussed in connection with the fuel employed following the steps by which progress has been made, even though some details of design may be alike in all or nearly all furnaces. The principles of furnace design developed in connection with furnaces having stationary hearths, *in-and-out* furnaces, are equally applicable to furnaces having movable and moving hearths and other labor saving furnaces. Furnace design will first be considered in connection with stationary furnaces, because from them other types have developed.

The design of a furnace depends upon the type of fuel employed and, also, upon the method of applying and distributing heat. Heat is transferred in three ways, namely, by conduction, by convection, and by radiation. Heating by conduction, that is by direct contact, seldom enters into steel-treating practice. Heat is transferred by convection, that is, through contact with hot gases or liquids, or by radiation, direct transfer through heat rays, or by both convection and radiation. The heat transferred by radiation increases with the fourth power of increase in temperature. Radiant heat is, therefore, more efficient at high than at low temperatures. For this reason, furnaces for hardening and other operations that require comparatively high temperature are designed to take advantage of radiant heat. Furnaces for tempering at comparatively low temperatures are heated by convection. In electric furnaces for the higher temperatures, heat is transferred directly by radiation; in furnaces heated with combustible fuel, heat is transferred by radiation and convection when comparatively high temperatures are desired.

Electric furnaces for high temperatures are heated only by radiation because of the nature of the source of heat, and heat can be evenly distributed if the heating elements are properly placed. On the other hand, coal-fired, oil-fired, and gas-fired furnaces are heated primarily by the gases of combustion, with radiant heat as a secondary source, at least until the furnace is heated to temperature. These gases pass through the furnace and out to the air, giving up heat on the way. This heat must be distributed evenly and with as little waste as possible. Methods of distributing and venting the gases may be somewhat alike with the three types of fuel, but the methods of applying the heat of combustion will differ with radically different types. Solid fuels require a distinctly separate fuel bed, but gas or oil may be burned directly in the working chamber (*direct firing*) as well as in a separate combustion chamber (*indirect firing*) that may be located just below the working chamber (*underfiring*) or above (*overfiring*). The term "overfiring" is sometimes used in place of direct firing in describing furnaces in which combustion takes place near the roof of the chamber.

The design of a furnace will, therefore, depend upon the method of heating, whether by radiation or convection or some combination of the two, and upon the methods for the distribution and venting of the hot gases of combustion, that is, upon the position of the combustion chamber and of the flues and vents, if heating depends upon combustion. The use of similar methods of distributing and venting these gases may be responsible for similarities in furnaces heated by different fuels, but the details of construction will differ in furnaces heated by different fuels, because dependent upon the nature of the fuel.

The process to which a furnace is to be applied must be considered in design. Some processes require a definite type of furnace. Cyaniding, for example, requires a molten bath. Likewise, the mechanical equipment of a furnace may limit the method of applying heat. A *walking-beam* furnace, for example, requires overfiring. When, however, no such limitations exist, considerable variation in design is possible. Furnace design began with stationary-hearth furnaces charged and unloaded by hand, and such furnaces were used long before mechanical equipment for steel-treating furnaces was contemplated. With furnaces having stationary hearths, the proper methods of applying and distributing heat have been developed.

A furnace mechanically equipped is, to all practical purposes, a stationary furnace that is provided with a moving floor or with outside means for moving the material in process over the floor. The addition of mechanical equipment to furnaces has had little or no effect upon the development of methods of applying and distributing heat, and will, therefore, be discussed separately.

Furnaces for Solid Fuel. Forge, Muffle, Bridge Wall.—Furnaces using solid fuel and, in fact, all furnaces for heat treating steel can be considered as a replacement and development of the open forge, once the only furnace for that purpose, and, to some extent, as a development from the forge. Open forges, similar to those used centuries ago, are still in service, and the general construction of such forges is illustrated in Fig. 80 A.

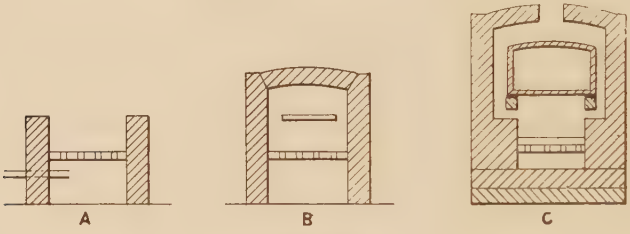


Fig. 80.

High temperatures can be obtained by forcing air through the fuel bed, temperatures that change rapidly as the supply of air varies and that are difficult to control. Because the control of temperature is difficult, the open forge is not a suitable furnace for heat treating.

Better control of heating can be obtained by covering the fuel bed with a steel plate upon which the material to be heated can be placed, out of contact with fuel, a practice of long standing that possibly began with the use of stone for a cover when iron and steel were scarce. This is the first step in providing a working hearth. If, now, walls and roof are built around the forge, as shown in Fig. 80 B, another step has been taken in the direction of modern furnace construction. The object of the enclosed forge is to provide a continuous supply of fuel to the fire bed. Enclosed forges are now used more for ease in supplying the fire bed with fuel than for heat treating. The fuel is fed to the fire through an opening in a side wall over which it

is banked, so that it is preheated as it is fed to the fire. The enclosed forge is serviceable for tool hardening.

A further advance from forge to furnace occurs when separate spaces are provided, one for the fuel, the other for the work in process. Such separation may be complete so that there is no passageway between the two spaces, as in the muffle furnace shown in Fig. 80 C, a very old type of furnace and one that is used for other purposes besides the heat treatment of steel. Muffle furnaces may be heated with gas, oil, and electricity without much variation from the construction shown in Fig. 80 C. The muffle is usually heated on all sides, excepting the end that is left open for charging and, also, the end opposite this opening. It is intended to exclude the gases of combustion, and material to be heated in the muffle receives heat by radiation only. The design of muffle furnaces varies but little with the fuel that is used, with the exception of electricity, for which no combustion chamber and no flues are required. Modern electric furnaces are sometimes called "muffle furnaces," although the heating units are within the chamber. In earlier types, the heating unit was wound around the outside of the muffle because protection was required for the unit.

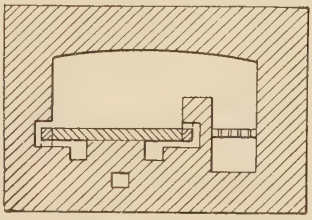


Fig. 81.

The muffle furnace has had little use in the industrial heat treating of steel because it is seldom necessary to prevent contact between the gases of combustion and the steel in process; in fact, they are usually of value in heating. In furnaces heated by solid fuel, the working chamber is usually separated from the fuel bed by a baffle wall over which these gases can pass. In Fig. 81 is shown in section the arrangement of a typical furnace heated by coal or coke, one that has had extensive use. Other types were built that differed from the type illustrated in the position of the flues, the height of the baffle wall, and minor details but kept the chambers in the same relative position, the fire box at the side.

The working chamber of the furnace illustrated cannot be heated uniformly throughout, because temperatures will be higher in proximity to the fire wall than at the other wall. The draft is toward the back, so that temperatures tend to be higher

at the back than at the front, sometimes much higher. This effect can be counteracted by making the bed of fuel deeper at the front than at the back. At best, control of temperature is difficult, and the rate of heating is variable because dependent on natural draft that varies with the weather. In such furnaces, heat is transferred to the steel being treated by radiation and convection.

In a more recently developed type of furnace, a single fire box is connected by flues with a number of chambers, these being heated by the hot gases from the burning fuel. The flow of these gases is controlled by dampers. Temperatures throughout each chamber can be quite uniform and can be easily controlled, but the rate of heating is usually slow because heating is largely by conduction and is subject to the variation of natural draft. The space required by a battery of heating chambers and fire box will sometimes prevent a convenient systematic arrangement of furnaces that will simplify handling. This type of furnace, however, is an improvement upon the older types.

Solid fuel is no longer used to any extent in the heat treating of steel, because the processes can be carried on with greater efficiency by the use of the other sources of heat. Local conditions may give some advantage to coal or coke, but oil and gas, particularly oil, and even electricity may be cheaper than coal or coke in spite of a higher first cost. More uniform heating and increased output can more than compensate for a higher first cost, uniform temperature meaning no waste of fuel in local overheating, and a more rapid rate of heating meaning an increased output. Rapid heating in furnaces depends upon the rate at which heat can be supplied, upon the number of heat units that can be made available in a given space in a given time. Solid fuel is comparatively sluggish in giving off heat. Uniform heating depends upon the even distribution of heat, and the nature of fuels such as oil, gas, or electricity permits flexibility in heat distribution. This, however, will be of little value without a properly designed furnace, one adapted to the particular fuel in use and one that permits a uniform distribution of heat.

Furnaces for Oil and Gas.—Furnaces properly designed for oil and gas did not come into existence as soon as these fuels replaced coal and coke; time and experience were required for their development. Furnaces for gas and oil developed side by side, much alike because of similar methods required for and

similar results obtained by their combustion. Because of the greater power of oil, combustion chambers are required to be larger in oil-fired than in gas-fired furnaces, and there may be minor differences in other details of construction. Because of the present prominence of oil, more effort had been spent on oil-fired furnaces, but construction will be much alike with oil or with gas. For these reasons, oil-fired furnaces will be given first place in discussion, with reference to gas when necessary. If the tables are turned and gas is given the place which it deserves, the principles will still be the same. Gas preceded oil as a fuel for heat treating, and furnaces for gas were developed from which some features of the oil-fired furnaces have been borrowed.

Development from Coal-fired Furnaces.—When oil became available for fuel, coal, and coke as well, was extensively used for heat treating. Coal-fired furnaces were often converted into oil-fired furnaces without change other than the addition of burners, for which holes were drilled through the outer wall of the combustion chamber, sometimes at the front and back but more frequently at the side so that the flame would strike against the baffle wall. Even after furnaces were built for oil exclusively, baffle walls were included in the construction of many, persisting as a transition stage of design. A few such furnaces will still be found.

Direct Firing. Overfiring.—A decided departure from the coal-fired furnace is shown in some of the earlier types of furnace for gas or oil that had but one chamber, a working and a combustion chamber combined, heated directly by the burners, which enter the chamber through holes in the furnace wall, direct firing. Direct-fired furnaces are of several types that differ principally in the position of the burners and of the vents, and upon such differences depends the value of the furnaces for uniform heating.

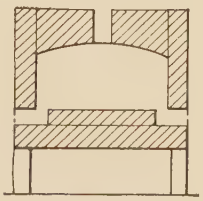


Fig. 82.

In Fig. 82 is shown a cross-section of a direct-fired furnace, one of the first types used with gas. This type has also been used with oil fuel. The direct venting is responsible for high-fuel consumption, and the direct contact between flame and material in process is responsible for difficulty in heating uniformly, especially if oil is the fuel. Better results will often be obtained by placing the burners at the ends of the furnace.

In more modern direct-fired furnaces for oil, the burners are placed at the top of the chamber, so that the flame will not play directly upon the material on the hearth, and the flues for venting start near the floor and go up through the walls to the top. The arrangement is indicated in the drawings of Fig. 83. One flue starts in one side wall, passes beneath the floor, and goes up through the opposite wall. The next flue reverses the direction so that in each wall intake flues and venting flues alternate, and the gases pass in opposite directions through adjacent flues beneath the floor. The position of the burners is important. In the illustration, the burner is shown in the side wall, firing across the furnace, merely to show its position near the roof. It is better and more common practice to place the burners at the ends, presuming a greater distance from end to end than from side to

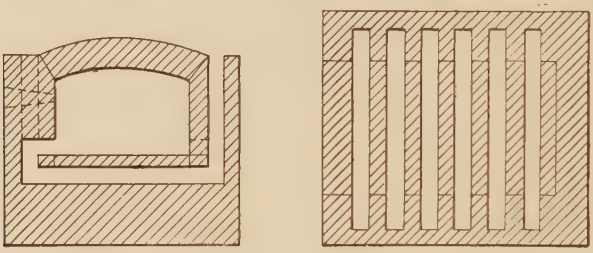


Fig. 83.

side, as is usual in furnaces. If the flame is allowed to strike the wall opposite the burner, a *hot spot* will be formed, and as the temperature of the portion of the hearth just below the burner may be below that of the rest of the hearth, the results may be varied, to say the least.

Direct-fired furnaces with burners well above the floor are sometimes termed "overfired;" "direct overfired" would be a descriptive term, because overfiring may be indirect. For indirect firing, a separate combustion chamber can be placed above the working chamber, the hot gases passing into the working chamber through holes in its roof, as illustrated in Figs. 101 and 104 (Chap. XII), a good arrangement for continuous furnaces, furnaces with a moving hearth. Overfiring is usually necessary in continuous furnaces, because the mechanical apparatus occupies the space below the hearth where a combustion chamber could be placed. Underfired furnaces can be used if the mechanical equipment does not so interfere.

Indirect Firing. Underfiring —Indirect firing has advantages over direct firing in uniformity of heating—local overheating is not so likely—and in the storing of heat-radiant heat in the combustion chamber, which can safely be heated to temperatures far higher than would be posssible in the working chamber. The combustion chamber serves as a reservoir of heat. The impor-

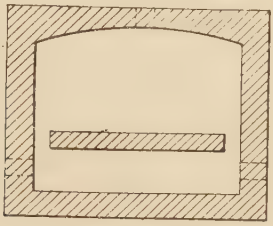


Fig. 84(*a*).

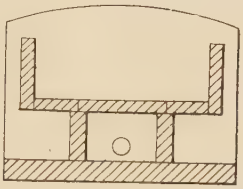


Fig. 84(*b*).

tance of these advantages will depend upon the parts to be treated and the results required.

Indirect heating is generally obtained by underfiring, the combustion chamber being placed below the hearth, as in Fig. 84 (*a*), an early type of underfired furnace. This is much like the direct-fired furnace of Fig. 82; adding a combustion chamber

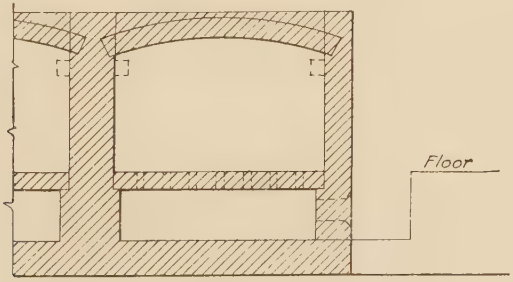


Fig. 85.

would make the two almost identical. There are no flues, only holes in the roof for vents. In early furnace practice, combustion took place at the bottom of the furnace, and vents were placed at the top, so that the hot gases went straight up and out—quite logical construction, as hot gas tends to rise. As already mentioned, modern practice has reversed this process to some extent by bringing the hot gases into the working chamber at the top

and removing them at the bottom. The added side wall shown in Fig. 84 (*b*), is one step in this direction.

Although indirect heating may be preferable in general heat treating, it is sometimes desirable to bring the hot gases from the combustion chamber into the working chamber by the shortest possible route, heating the charge almost directly from the combustion chamber. In Fig. 85 is shown a furnace that provides an almost direct connection between the two chambers, a furnace that has been used successfully for *box annealing*. The floor is of tile, perforated to permit the passage of hot gas from the combustion chamber beneath to the working chamber above. The containers indicated are large and occupy so much space that rapid uniform heating cannot be obtained easily by overfiring. The method illustrated takes advantage of the reservoir of radiant heat in the combustion chamber and of the natural upward flow of hot gas. A reasonably uniform distribution of heat is obtained by proper spacing of the perforations. This is one example of special furnaces that are sometimes required for a particular production. The greater part of production in heat treating, however, is usually handled in furnaces for which methods of distributing heat have become more or less conventional.

Semimuffle Furnaces.—The control of heat distribution in an underfired furnace of modern construction is shown in Fig. 86, a furnace somewhat resembling the direct-fired furnace of Fig. 83. In this underfired furnace, all flues are in the side walls, some leading from the combustion chamber to the working chamber, entering just below the roof; others, from the working chamber to the outside. In each side wall there are usually three venting flues, one near each corner, and one in the center. The incoming flues are usually two in number, each placed between two venting flues. In small furnaces, the central venting flue may be omitted. To furnaces of this type the name "semimuffle" has been given.

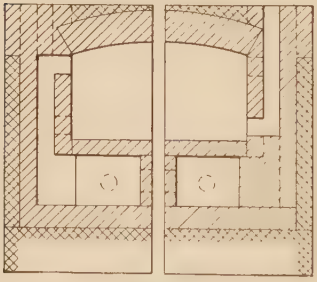


Fig. 86.

Another type of semimuffle furnace is shown in Fig. 87, plan and cross-sectional elevation. The flues from the combustion chamber of the furnace of Fig. 86 have been replaced by an

opening between the hearth wall and the outside wall, and the outgoing flues have been placed in the back wall with auxiliary flues at the front. For the same width of hearth this furnace will be wider than the furnace of Fig. 86, and more brick will be required.

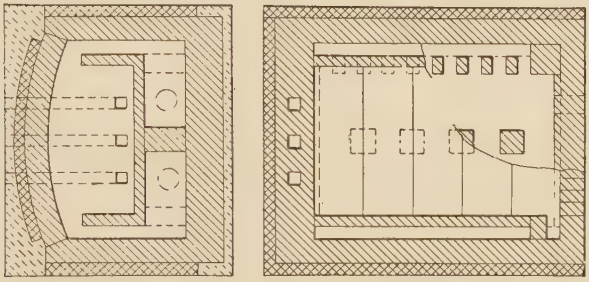


Fig. 87.

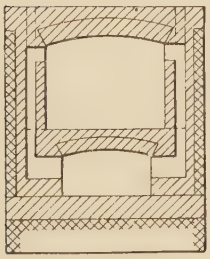


Fig. 88.

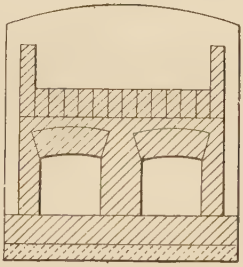


Fig. 89.

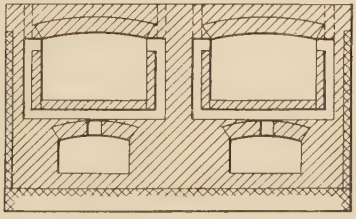


Fig. 90.

In both semimuffle furnaces just considered, tile floors have been shown, but, instead of tile, a brick arch may be used, as in Fig. 88, the design being otherwise like that of Fig. 86. Similarly, the tile floor of the furnace of Fig. 87 may be replaced by a single arch, as in Fig. 88, or, perhaps, by twin arches, as shown in Fig. 89, a construction sometimes preferred to the

single arch when a wide distance is to be spanned. In Fig. 90 is an arch furnace with a tile floor, a compromise between the two that has been proposed but not accepted to any extent.

Twin and Block Furnaces.—Figure 90 shows *twin* furnaces, a combination that is commonly used to save in the cost of construction and to reduce the floor space required. Block construction has the same advantage over twin construction, but twin is sometimes preferred because it more readily permits passageways between the furnaces. There will be no interference between twin furnaces or furnaces in blocks; one may be heated without affecting the other or others if the dividing wall is from 13½ to 18 in. thick, the thickness depending on the temperatures employed.

Arch and Tile Floors. Advantages and Disadvantages.—Semi-muffle, underfired furnaces with stationary hearth are extensively used because so well adapted to general production. The various types of such furnaces may be much alike in the method of guiding the flow of hot gas and yet differ considerably in the details of construction. Examples illustrating differences in floors have been shown; in Figs. 83 to 87, the floor is of tile; in Figs. 88 and 89, the floor is supported on an arch. Either type of floor may be used without necessarily affecting the other details of construction, excepting, perhaps, the supports. For example, the furnaces of Figs. 86 and 87 will be alike if the floors are removed. The choice of tile or arch often depends upon the personal opinion of the individual designer, and this opinion is usually based on a comparison of the advantages and disadvantages of each. The advantages generally claimed for tile floors are:

The comparatively low cost of building and renewing.
Ease of rebuilding and repairing.
The short time required to heat.

The disadvantages are stated as:

Comparatively short life.
The large number of joints, where leaks can occur.
The necessity for supports in the combustion chamber of wide furnaces.

Some of the advantages claimed for arch construction are:

Long life.
Strength.
The combustion chamber contains no obstructions.
Storage of heat in the arch.

The disadvantages include:

Comparatively high cost of construction and replacement.
Length of time required to build.
Length of time required to bring to temperature.
Care required to provide and to keep a smooth, level floor.

The importance of these various advantages and disadvantages depends upon the operating conditions. If operation is continuous for a long period, several months, perhaps, the arch may be preferred; if intermittent, so that repairing will not interfere with production, tile may be more desirable. Tile heats through quickly; the arch, slowly; but the arch will hold heat for a longer time. Tile floors are sometimes burned through rapidly; the arch is too thick for such rapid deterioration. The effect of wear and tear on the floor due to unloading and loading is presumed to favor the arch, but this is not of great importance; the floor of either furnace can be protected by steel plate or strips, a common method. Tile has the most important advantages—comparatively low cost and greater ease of repair—and because of these, tile floors are used more than the arch.

Combustion Chamber and Flues.—Floors may differ and so may roofs, hearth walls, and other portions of the furnace, but the system of combustion chamber and flues—the heart and arteries—of a semimuffle, underfired furnace will not vary to the same extent, for they are the basis of a general design. The starting point of a system of flues and vents in either direct- or indirect-fired furnaces is the combustion chamber. In the direct-over-fired furnace, no provision is made for a combustion chamber, although recesses or even baffles may be supplied to direct the flow of gases. In the indirect-fired furnace, however, the combustion chamber, either above or below the hearth, is an important feature. The arrangement of flues, supports, baffles, and splash brick affects the flow of gases and, therefore, the uniformity of temperature, but the size of the combustion chamber often determines the amount of production and the life of the furnace as well. In nearly all heat-treatment processes, the amount of production depends to a greater or lesser degree upon the time necessary to bring the charge to the required temperature, this time, in turn, depending upon the rate of heat transfer from the burning fuel to the charge. To a large extent, this rate depends upon the amount of fuel that can be burned and, within the limits of the capacity of furnace and of flues, the amount of

fuel that can be burned will depend upon the size of the combustion chamber. If, therefore, the combustion chamber is small, production will be correspondingly low. If the flue capacity is large, it is possible to increase production by *crowding* the furnace, but if this is carried too far, rapid deterioration of the hearth and walls will result. The combustion chamber should be large enough to allow a fuel consumption somewhat below the capacity of the flues to carry off the waste gases.

The length and width of the combustion chamber are controlled by the dimensions of the hearth. The variable dimension is the height, upon which the capacity of the chamber will, therefore, depend. The proper height will depend upon the fuel, the capacity of the furnace, and the rate of heating required. Under the same conditions, furnaces intended for oil require much higher combustion chambers than furnaces intended for gas, unless the gas is to be delivered in large quantities under high pressure, oil supplying proportionately far more heat units than gas.

In early types of underfired furnace with oil fuel, the height of the combustion chamber is much less than in furnaces of recent design. A fair average of height was once, perhaps, 6 in.; now 12 to 15 in. is the average. The combustion chamber in small furnaces will be about 10 in. high; in large furnaces, 15 to 20 in. high. When gas is the fuel, the combustion chamber can be lower than for oil, the usual range being from 7½ to 17½ in. With either fuel, and especially with oil because of the intense heat that can be obtained, it is better to build too large than too small. An increase in the height if the combustion chamber has often resulted in more uniform heating, lower fuel consumption or increased production, and longer life for the floor and for the furnace.

The capacity of the flues that lead from the combustion chamber and of the venting flues should be large enough to carry all of the gases formed in the combustion chamber when the burners are operating at full capacity. The cross-sectional area required for flues can be calculated, but in practice the area of the flues will be much larger than the area theoretically required. Some idea of the allowance made for flues can be gained by considering the furnaces already discussed. In Fig. 91, a photograph of a semimuffle furnace, also shown in cross-section in Fig. 86, the hearth is 4½ by 5 ft. In the photo-

graph, five flues leading from the combustion chamber to the working chamber can be seen near the roof, ten in all, each 4 or 4½ by 5 in. The venting flues, three on each side, are of the same dimensions. In the furnace of Fig. 87, there are no flues from the combustion chamber, but there are three venting flues in the back wall and two in the corners at the front, each 4 by 5 in. This is required for a hearth area of from 25 to 30 sq. ft. For a smaller hearth, perhaps 4 by 5 ft, the center flue in the back wall can be omitted. The area required for flues varies with the amount of fuel to be burned, but these are representative examples.

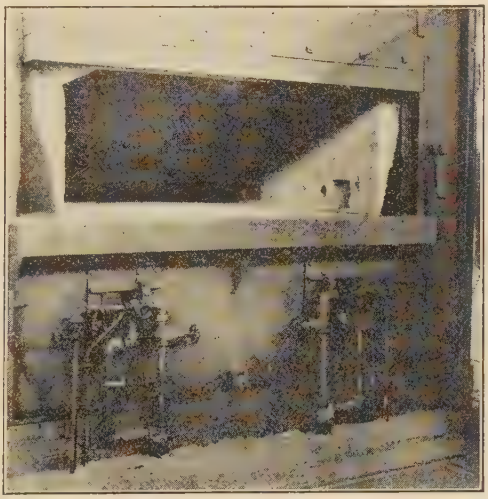


FIG. 91.—Semimuffle oil-fired furnace.

More venting flues than actually required are very desirable, because it is possible to close them off partly or entirely, but an increase of flue capacity requires rebuilding. In the furnace of Figs. 86 and 91, the center venting flue is seldom needed and is, therefore, closed off by a tile or brick, but it is there if needed. If the venting flues at the back draw more than their share of gas, so that the temperature is higher at the back than at the front, these flues can be partly closed, thus throwing more gas into the front flues. The furnace of Fig. 87 can be controlled in the same way. Furnaces that are apparently similar sometimes differ in the distribution of heat, because some flues may have more draft than others, and such flues will not always be in the same position in these furnaces.

Position and Number of Burners.—In semimuffle, oil-fired furnaces of the types described, the burners are usually placed at the front or at the back or at both front and back. Side firing is not necessarily objectionable, but the other is usually preferred, because the distance from front to back is greater than that across and, also, because the supports can be better arranged to allow a clear space for combustion. These furnaces may be heated by one burner, placed at the front or back in the center; or by two, usually at both front and back, staggered; or by four, two in front and two in back, as illustrated in the photographs of Figs. 91 and 171, front and back of the same furnaces. One burner is more desirable than several if automatic control is employed, but a larger number will heat more rapidly and with less deterioration of the furnace. A furnace properly designed can be maintained at uniform temperature with any one of a set of burners, using the others to speed up heating. Gas-fired furnaces require more burners than oil-fired furnaces because of the lower calorific value of gas and are usually side fired, as shown in the photographs of labor-saving furnaces in the next chapter.

Roof and Walls.—The number and position of flues and burners depends upon the type of furnace, but the construction of the shell of the furnace, the roof and walls, will be, with a few exceptions, much the same for all heat-treating furnaces. The dimensions of a furnace will vary but will usually be in multiples of standard-size fire brick, 9 by $4\frac{1}{2}$ by $2\frac{1}{2}$ in., because of convenience, and general practice is in accordance. This is not a hard-and-fast rule, because brick of other dimensions can be obtained and cutting is possible. Methods of supporting and tying roof and walls will be much the same in all furnaces, because they follow principles that are general. The materials of construction, both refractory and insulating, will be the same because of similar requirements. The conditions that govern the dimensions of the hearth and its distance from the floor are not dependent upon the type of furnaces, nor are the conditions that govern furnace dimensions in general.

For the purpose of retaining heat, the combustion and working chambers of a furnace are enclosed by roof and walls. These may also serve for storing and giving off radiant heat. The roof of a furnace is usually built in the form of an arch that is the arc of a circle, and the height of the arch is based upon the

length of the radius of that circle. If the radius is short, the arch will be high, the limit being a semicircle with a radius equal to half the width of the furnace. If the radius is long, the arch will be *flat*. The flat arch is usually preferred. The thickness of the arch in a heat-treating furnace is usually from 9 to 18 in. although 13½ in. is the more common maximum, these figures being based on brick dimensions. In heat-treatment furnaces of older types, sectional arches were sometimes used, following the practice of the malleable-iron foundry for air furnaces. Each section is composed of a steel or iron casting that holds a row of fire brick. Unless such a roof is covered, thus losing the advantage of the removable sections, the loss of heat by radiation from the roof is high, and the thermal efficiency is, therefore, low. In addition, the large amount of heat given off causes a high room temperature, very uncomfortable for the operators. Such roof construction is now rarely used for heat-treating furnaces.

The walls of a furnace are supports for the roof as well as being an enclosure for the combustion and working chambers. The thickness of the walls varies from 9 to 18 in., depending upon the working temperature of the furnace. For the higher ranges, from 1400 to 1800° F. (760–980° C.), walls will be from 13½ to 18 in. thick. In the combustion chamber of an under-fired furnace, additional brick may project into the chamber to furnish a support for the floor whether arch or tile, unless separate supports, as in Fig. 87, are used. The addition of this support increases the thickness of the wall around the combustion chamber, where it is desirable.

Roof and Wall Support. Beams and Tie-rods.—The walls furnish support for the roof and are, therefore, usually given assistance in this support. Heating and cooling are accompanied by shrinkage and expansion of the brickwork, and the strength of the brick is reduced by heat. The walls tend to push outward under the load of the arch, and, unless held, the roof may fall. Walls are sometimes braced by I-beams, placed at intervals along the wall and connected with other I-beams, similarly placed along the other wall, by tie-rods above and below the furnace. Additional suppport may be obtained by strips of boiler plate extending along the side walls of the furnace, held in by the I-beams. Even better support can be obtained by enclosing the walls with heavy plates of cast iron or steel,

a method that is illustrated in most of the photographs of furnaces in this and in the next chapter, for example Figs. 91, 92, and 105 to 107. Such a framework is sometimes sufficient for retaining the walls and roof of a small furnace, but more support should be provided if the roof is heavy, as by the additional vertical beams and the tie-rods of the various furnaces illustrated.

Refractories.—The life of a furnace is dependent to a considerable extent upon the materials of which it is built, particularly upon the quality of the refractory brick. Fire brick for heat-treating furnaces may be classed very loosely in three types: one having a very high resistance to heat, suitable for combustion chambers, floor supports, and the lining of flues leading from the combustion chamber; one having a somewhat lesser resistance, suitable for lining working chambers and outlet flues; and one that is suitable for comparatively low temperatures and used for foundation and walls. Unless a large number of furnaces is to be built, only the first two grades will be used. In addition to fire brick, brick composed largely of silicon carbide are being used extensively in places where the temperatures are relatively high, for example in furnaces for the hardening of high-speed steel. Such brick are much more expensive than fire brick and are used only when the extra cost will be balanced by the longer life. Silicon carbide conducts heat rapidly and is finding an application in furnaces in which heat is transferred to the charge by radiation only. Furnaces of this type have not as yet been applied to general heat treatment.

Heat-insulating Materials.—One object of the shell of a furnace is to retain heat, and losses by radiation from the walls and roof can be decreased by making them thicker, but this increases the cost and is often inconvenient. Better results can be gained by using insulating materials, thus avoiding the necessity for heavy walls and roof. Insulating materials owe their properties largely to enclosed air, *dead* air, scattered in small pockets throughout. Asbestos and magnesia are common insulating materials, but these are seldom used in heat-treating furnaces because expensive and not easy to handle. The insulating materials most generally used for heat-treating furnaces are known by the trade names "cork brick" and "Silo-cel" and are usually applied in the form of brick, although

powder is sometimes used. These brick are placed on the roof of the furnace and on the outside of the side and back walls, as illustrated in Figs. 86 and 87. The thickness of insulation required will depend upon the thickness of the firebrick and upon the temperatures to be employed in the furnace but is usually either 2½ or 4½ in., following the dimensions of the brick. Proper insulation will soon pay for itself in the saving of fuel, not to mention better working conditions.

Furnace Dimensions and Production.—A furnace is built not only for economical and uniform heating, but also for efficient production, so that the charge to be heated and the method of loading and unloading are factors in its design. The dimensions of the hearth, and, therefore, the dimensions of the furnace, may depend upon the size of the pieces charged; large pieces will require a large furnace, and small pieces can be heated in a small furnace. Small furnaces may sometimes be desirable but are usually inefficient for quantity production. The average production does not require a very large furnace because of size but does require a furnace large enough and not too large for efficient production. The dimensions of the hearth are limited, to some extent, by the time required for loading and unloading, which depends, in turn, on the method of handling. Two men can load and unload a furnace more rapidly than one and, therefore, can operate a larger furnace. To determine the most efficient size, a comparison can be made between various combinations of load and furnace dimensions, including handling and operating costs.

Such a comparison is particularly useful in selecting the dimensions of the hearth for carburizing in containers. A balance must be struck between the size of the container and the size of the furnace, and the basis of selection will be the number of individual pieces that can be put in the furnace. An estimate of the number of pieces that can be carburized in each of the possible combinations of box sizes and furnace sizes will determine the proper combination to use. For such estimates, *cut-outs* to scale are very convenient. A balance can also be struck between boxes of different size to determine the furnace dimensions most suitable for all. Sometimes, these estimates will show that furnaces of two different sizes will be more efficient than furnaces of one size. A careful analysis usually pays; it is better to select the proper size than to guess

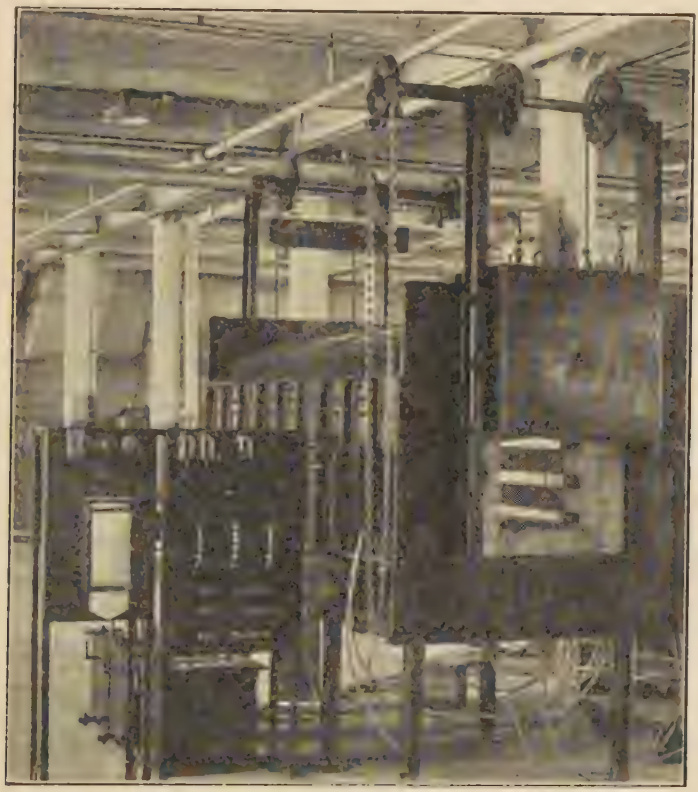
at it and then find that 4 or 5 in. more added to the width of the hearth would increase production by 20 per cent.

Distribution of the Furnace Charge.—Furnace efficiency or, rather, the efficiency of furnace operation also depends upon the distribution of the charge on the hearth. As a general rule, a furnace charge should consist of one layer if rapid heating is desired. Heat is transferred much more rapidly by radiation or by convection from the hot gases than it can be transferred through steel. To double the number of pieces in a furnace by using two layers instead of one may require more than twice the time for heating. To take full advantage of the radiant heat of the furnace and of the hot gases, containers should be spaced well apart; for carburizing boxes of average size, 3 to 4 in. is required. Nearly all furnaces will have a higher working chamber than the average charge requires because of the arrangement of flues and vents, and the extra space is a temptation for large loads.

Electric Furnaces.—The design of electrically heated furnaces offers no difficult problem, because no combustion chamber and no flues are required. Proper distribution of the heating elements for uniform heating and heavy insulation to reduce loss of heat by radiation are the principal requirements. The heating element is now usually nichrome, but carbon resistors were once used to a considerable extent. A new heating element consisting principally of silicon carbide has been introduced and has been applied to the heating of small furnaces. The material is usually in the form of rod. Nichrome is used in the form of wire, ribbon, and in grids, each form having its advantages and disadvantages. Figure 92, an electrically heated furnace of the in-and-out type, illustrates one method of placing the heating elements in the roof and walls. Heating elements may also be placed below the floor.

Figure 93 (*a*) is a photograph of an electrically heated furnace of the *pot* type. This particular furnace is equipped with a pyrometer recorder, and the couple is so placed that the critical temperature of the steel being heated will be indicated on the record. This is called the "Hump method," the name being derived from the change of direction of the curve. This furnace is applied to the production of parts that can be placed on spindles or otherwise loaded so that the critical temperature can be easily detected, but it is also extensively used for hardening tools. The couple may be placed within the charge but out of contact or may be in direct contact if only one piece is charged.

Two methods of placing the couple are shown in Fig. 93 (*b*) and (*c*). A sample curve is shown in Fig. 93 (*d*). The cold charge lowers the temperature of the furnace to 700° F. (*A*). The application of heat then raises the temperature of the furnace and charge until the critical change occurs, this beginning at C and ending at D.



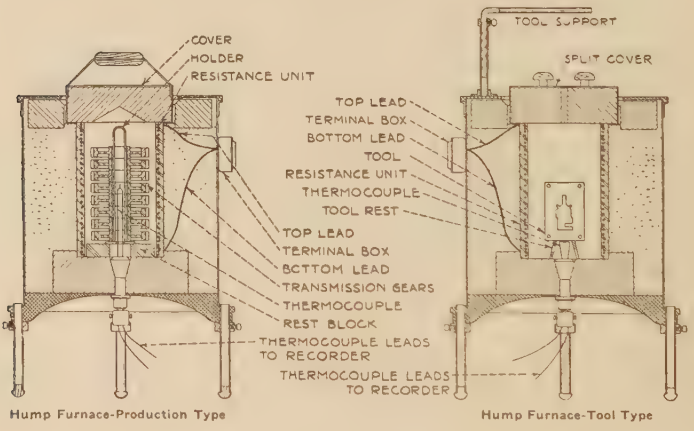
(*Courtesy Electric Heating Apparatus Co.*)
FIG. 92.

Furnaces of the same general type but intended for drawing are shown in the photograph of Fig. 93 (*e*). Drawing temperatures are low, and drawing furnaces, therefore, do not depend upon radiant heat. The heat transferred by radiation increases with the fourth power of the increase in temperature, and radiation is, therefore, more efficient at high temperatures than at low. In this electrically heated drawing furnace, therefore, transfer of heat is obtained by convection, heated air being

drawn through the furnace by means of a fan. The method of circulating air is illustrated in Fig. 93 (*f*).

(*a*)

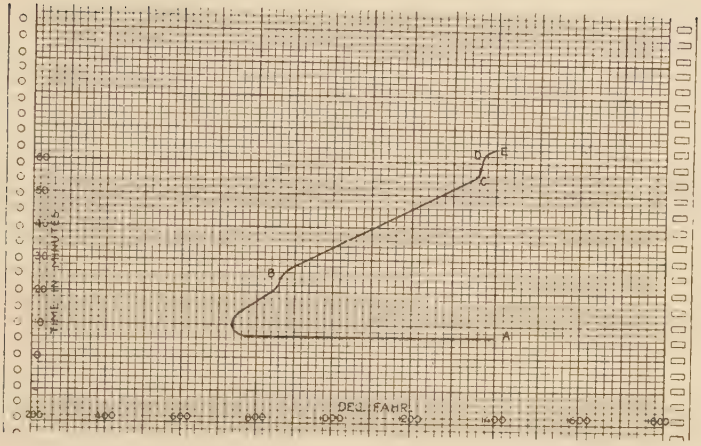
Fig. 93. (*a*)—Electrically heated hardening furnaces. (*Courtesy Leeds & Northrup Co.*)



(*b*) (*c*)

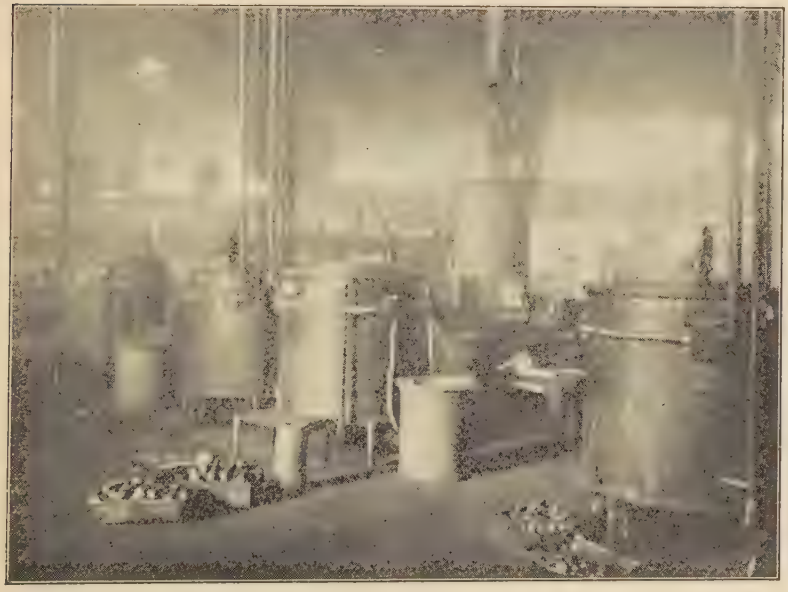
Fig. 93 (*Continued*).—(*b*), (*c*) Hump method electrical furnace.

Requirements for Economical Operation.—The electric furnace, excepting some designed for tempering, is practically a muffle furnace heated by radiation from a heating element. This



(*d*)

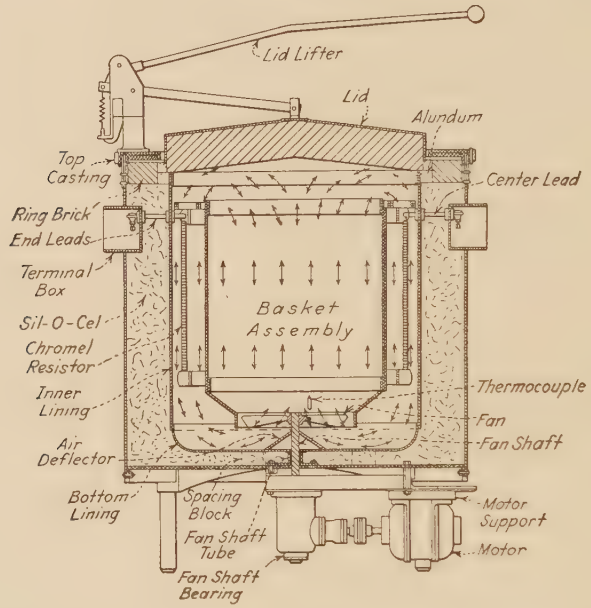
FIG. 93 (*Continued*).—(*d*) Chart showing "Hump" at C to D. (*Courtesy Leeds & Northrup Co.*)



(*e*)

FIG. 93 (*Continued*).—(*e*) Electrically heated drawing furnaces. (*Courtesy Leeds & Northrup Co.*)

element, in the form of rod, ribbon, or cast grids, is placed within the muffle, and the transfer of heat is, therefore, direct. The principal problems in designing the electric furnace are connected with the proper placing of the heating element and the reflection of heat, particularly from the roof. The heating element may be placed in the side walls, roof, and floor, as in Fig. 100, but many designers prefer to place them in the side walls only because a more even distribution of heat can be obtained. The arrange-



(*f*)

FIG. 93 (*Continued*).—(*f*) Section of electrically heated pot furnace for tempering, arrows show direction of air current. (*Courtesy Leeds & Northrup Co.*)

ment depends, to some extent, upon the charge to be heated. Heating elements are sometimes placed below the charge, particularly if there is no floor, this being replaced by a pair of beams or rails along which the charge is moved.

Alloys of nickel and chromium are the principal materials for heating elements at present, although silicon carbide is being used in small furnaces. Some difference of opinion exists with regard to the proper shape of the element, but ribbon or cast grids are more common than rod. Ribbon is formed to shape as desired. The temperature of the heating element

should not be too high, otherwise rapid deterioration or sudden failure may occur. In expensive equipment, provision is often made for controlling the temperature of the heating element. The temperature is usually controlled by the current passed through the element, and the usual allowance is 8 watts per square inch. Nickel-chromium elements should not be *forced*, but 10 watts and sometimes 12 per square inch are occasionally permissable for short periods.

The electric furnace may be preferred for reasons connected with the quality of the product but must usually compete with furnaces heated with combustible fuels on a basis of actual cost of operation. The electric furnace can be placed in the production line, thereby avoiding transfer for long distances. Furthermore, less labor may be required because of the greater ease of control. On the other hand, the electric furnace will be at a disadvantage in the unit heat-treating department, although its high efficiency will sometimes balance the higher cost of heat units, as illustrated in the discussion of fuel. Because of the loss of heat in conveyors, electric furnaces of the pusher type or of the type charged by means of special machines are more efficient than conveyor furnaces. This statement is true for furnaces heated by any fuel. Before the electric furnace is given preference over other kinds, an accurate comparison of cost should be made, one based upon efficient furnaces, and one that takes into account the possibility of increasing the efficiency of handling with furnaces using combustible fuel.

CHAPTER XII

BATH AND LABOR-SAVING FURNACES

Bath Furnaces. Advantages and Disadvantages.—Molten baths, first used in a small way for cyaniding, end hardening or softening, or heating small tools to be hardened, have been applied extensively to large production. In some plants, the hearth furnace was almost entirely replaced by the bath furnace for both hardening and drawing, and bath furnaces of large size were developed. Pots 2½ ft. long, 8 ft. wide, and 15 to 18 in. deep are not uncommon. The bath furnace competed successfully with the in-and-out hearth furnace but is not so successful in competition with the continuous furnace when production is large. As compared with the stationary-hearth furnace, the advantages of the bath furnace are:

Quicker transfer of heat.
Greater uniformity in heating.
Easier handling of the parts in process.
Greater output for the same amount of labor.
Cleanliness, freedom from scale.
Less floor space required for the same output.
Lower cost of furnace and of repairs.

The disadvantages are:

Higher fuel consumption.
Cost of maintaining bath.
Cost of maintaining pots.
Time required for melting.
Danger of fumes and of splashing of molten material.

Operating Requirements.—The disadvantages of the molten bath can be lessened by equipping in accordance with the operating requirements. Baths should be covered by hoods equipped with ventilators, a legal requirement in most states. Parts to be heated should be dry before entering the bath, so

that splashing will be avoided. Preheating before placing in the bath is sometimes an advantage, and the waste gases can be used to dry or to preheat. If drawing follows hardening, the heat from the waste gases of the first heating bath can be used to heat the drawing bath, possibly supplemented by direct heat. Preheating is generally required if the bath is small to avoid a large drop in temperature and freezing of the material of the bath in contact with cold steel but is not so necessary if the bath is large. With proper protection for the operators and utilization of the waste heat, bath furnaces can be operated economically and without much difficulty.

The Two Types of Molten Bath.—Molten baths are of two types, the lead bath and the salt bath. No fair comparison of the advantages and disadvantages can be made because of the widely varying operating conditions. There are, however, certain distinct differences that should be noted between lead and salts. Lead, for a given volume, weighs about ten times as much as salts. Steel floats on lead but sinks in salt mixtures, so that covers or weights are required if lead is used. Lead has a low melting point in comparison with that of salt mixtures used for hardening but has a high melting point in comparison with salt mixtures used for drawing. These mixtures, however, are expensive. Other comparisons will be evident when the different types of bath are discussed.

The Lead Bath.—Lead, melting at about 620° F. (327° C.), can be used for heating to temperatures between 900 and 1550° F. (480 and 845° C.) but is too volatile for extended use at higher temperatures. Lead baths are used for hardening and also, for drawing in the range between 900 and 1200° F. (480 and 650° C.). Molten lead is easily oxidized, and the oxides formed are volatile, much more so than the lead itself. Molten lead is, therefore, kept covered with charcoal, which not only acts as a cover but also reduces to lead any oxide formed. Salt mixtures that melt below the range of temperature within which the lead bath is to be maintained are also used for a cover to prevent oxidation of the lead. Lead oxide is poisonous, and covers that prevent its formation are necessary for the protection of the operators. Uncovered molten lead soon becomes saturated with lead oxide, a strong oxidizing agent that will remove carbon from steel. Steel heated in a lead bath saturated with oxide will be rapidly decarburized at the surface. A bath that contains oxide can be

cleaned by *poling*—stirring with sticks of wood. Green wood is preferable because of the agitation caused by the gases formed.

Salt Baths and Compositions.—Salt baths vary in composition because of the number of mixtures available and because mixtures of different melting points are required. Salt baths for hardening will differ in composition from baths for drawing. Baths intended for hardening can be divided into two classes—mixtures containing sodium cyanide and mixtures without cyanide. Baths containing cyanide can be used for cyaniding as well as for heating. Representative compositions of mixtures containing cyanide are as follows:

Representative Mixtures of Salts and Cyanide

Sodium cyanide	20	20	20	20	40	40	75	20
Sodium chloride (salt)	40	32	....	30	30	60	25	40
Sodium carbonate (soda ash)	40	48	....	30	30	....	....	20
Potassium carbonate	....	....	80	20	....	....	....	20
Melting point:								
Degrees Fahrenheit	1130	1090	1160	1080	1080	1240	1020	1040
Degrees Centigrade	610	588	627	582	582	670	550	560

Mixtures without potassium carbonate are less expensive than mixtures containing that salt, but it is one of the principal ingredients in mixtures that do not contain sodium cyanide, of which examples follow:

Salts for Heating Bath without Cyanide

Sodium chloride (salt)	60	40	50	40	40	35
Sodium carbonate (soda ash)	....	15	15	40	60	65
Potassium carbonate	40	45	35	20		
Melting point:						
Degrees Fahrenheit	1090	1060	1060	1080	1180	1150
Degrees Centigrade	588	570	570	582	638	620

These baths are primarily intended for hardening but may be used for drawing if the temperature required is at least 50° F. above the melting point. For drawing temperatures between 400 and 1000° F. (205 and 540° C.), the nitrites and nitrates of sodium and potassium are employed, and representative compositions follow:

Drawing Baths

Sodium nitrate	60	55	55
Sodium nitrite	...	45	45
Potassium nitrate	40	55	
Melting point:			
Degrees Fahrenheit	425	300	430
Degrees Centigrade	218	150	220

Other combinations are possible of which a number have been published in tables of physical constants.

Materials for Pots.—The pot is the backbone of the molten bath, for upon its life depends a good share of the cost of the process and freedom from delays in production. To replace a worn-out pot is not difficult, but it is not always so easy to remove salt or, worse, lead that has leaked from the pot into the furnace and solidified. Pots were once made of cast iron, and later malleable iron was employed, but neither lasts long at high temperatures. The cast-steel pot has a comparatively long life, but pots of nichrome or other alloys far outlast steel when exposed to high temperatures. Steel pots, however, are satisfactory for use at the lower drawing temperatures.

Design of Pots and Furnaces.—The life of a pot is dependent on design as well as on material. Pots with sharp corners were replaced by pots having large fillets and, eventually, by pots with round bottoms. Corners are the weak spots of a casting and at high temperatures are quickly worn away. Rounding the bottom of a pot reduces the space within, and a greater depth may be required, but this loss will be more than repaid by the increased life of the pot.

The life of a pot for a molten bath is also dependent on the design of the furnace and particularly upon the arrangement of the burner or burners and the distribution of heat. If the flame is allowed to strike directly upon the pot, local overheating will shorten the length of service. Design has, therefore, been largely directed toward preventing contact of the flame and the pot, not a simple matter in the small combustion space that is usually available. In heating small, round pots, the burner may fire directly into the space between the pot and the wall of the furnace but will be placed at an angle to prevent direct impingement and obtain a flow of the hot gas around the pot.

Further improvement in the design of pot furnaces has been in the direction of providing a separate combustion chamber.

Furnaces for Molten Baths.—Figure 94 illustrates pot furnaces of an early type, round pots placed in the combustion chamber. The arrangement shows a preheating chamber heated by the

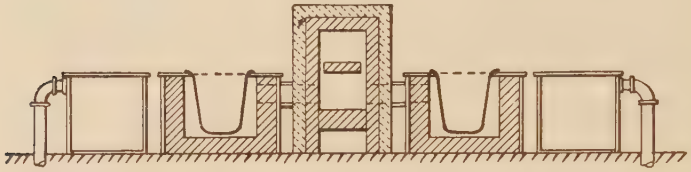


FIG. 94.—Old type lead bath furnace with preheater.

waste gases from the furnaces and is suitable for rapid production. The parts in process pass from the preheating chamber into one pot for further preheating and then into the second pot, which is held at the hardening temperature. This method, once used extensively, is now practically obsolete for large production.

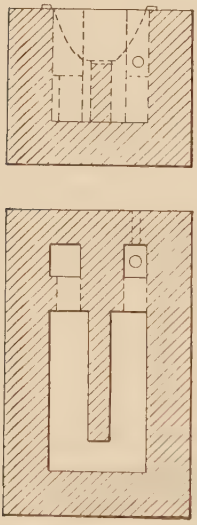


FIG. 95.—Lead bath furnace.

Figure 95 shows the plan and cross-sectional elevation of a rectangular bath furnace. The pot is placed in the combustion chamber, and a baffle wall in the center of the chamber is provided for uniform distribution of heat. Figure 96 shows a large furnace of the same type. In Fig. 97 is shown a bath furnace with separate combustion chamber into which the burner fires vertically. An auxiliary air blast aids in combustion and directs the hot gases into the heating chamber. In Fig. 98 is shown a bath furnace that is much like the hearth furnace in construction. The separate combustion chamber is below and separated from the heating chamber by a roof—tile or arch—tile being illustrated. The hot gas passes from the combustion chamber into the heating chamber through flues at the sides and is drawn off through a flue at the front. Such furnaces are often built in pairs, one for hardening, the other for drawing, and the waste gases from the hardening furnace used to heat the drawing furnace, at least in part. The general construction of a small lead pot, including a

cover to hold the lighter steel below the surface of the lead, is illustrated in Fig. 99.

In designing bath furnaces, the pot should be supported on flanges at the top, as illustrated in the sketches, and should not

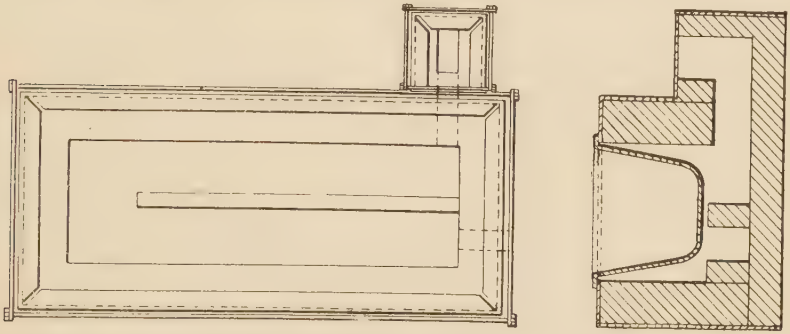


FIG. 96.—Large lead bath furnace.

be allowed to rest on the bottom. Space should be left between the bottom of the pot and the baffle wall or floor of the furnace to allow circulation and to avoid cold spots. The hot gases

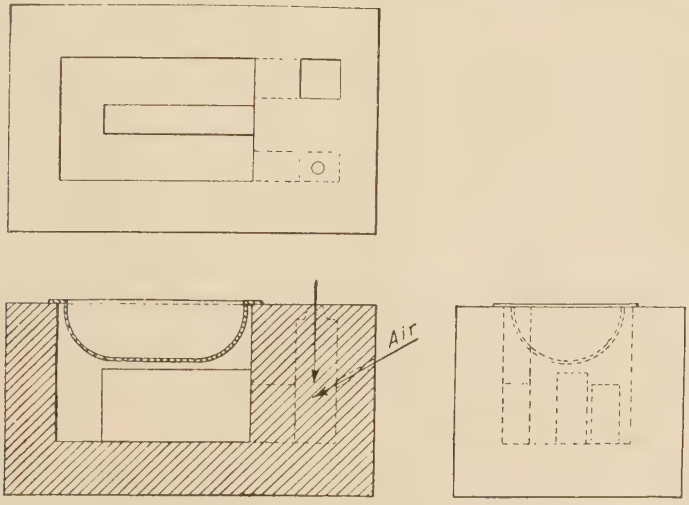


FIG. 97.—Lead bath furnace.

should be so distributed that the pot will be heated uniformly. One burner of the proper capacity is satisfactory if oil is used for heating, even if the furnace is large.

The bath furnace is more expensive to operate than the hearth furnace because of the added cost of maintaining the bath and pots and, therefore, must do more work with the same amount or with less labor required. The bath furnace is required for cyaniding and may also be necessary for cleanliness—freedom from scale—but whether or not it is to be preferred to the hearth furnace will depend upon comparative cost. The output of the bath furnace will vary with size, weight, and shape, so that no definite rule can be given by which a comparison of cost can be made. As compared with the in-and-out furnace, the cost of heating rather large parts will be less and of heating small parts,

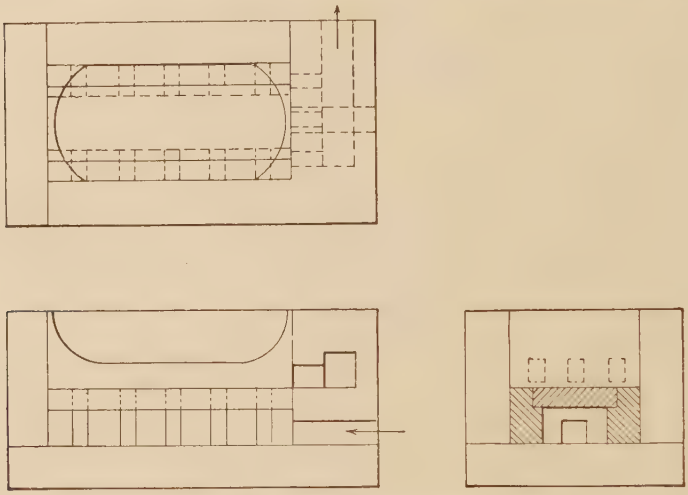


Fig. 98.—Lead bath furnace.

more. The bath furnace has an advantage over the hearth furnace for drawing because of the greater uniformity of temperature, and the additional cost of operating will often be more than balanced by the fewer rejections for hardness that require retreating. A comparison of cost is best made by trial of both methods of heating.

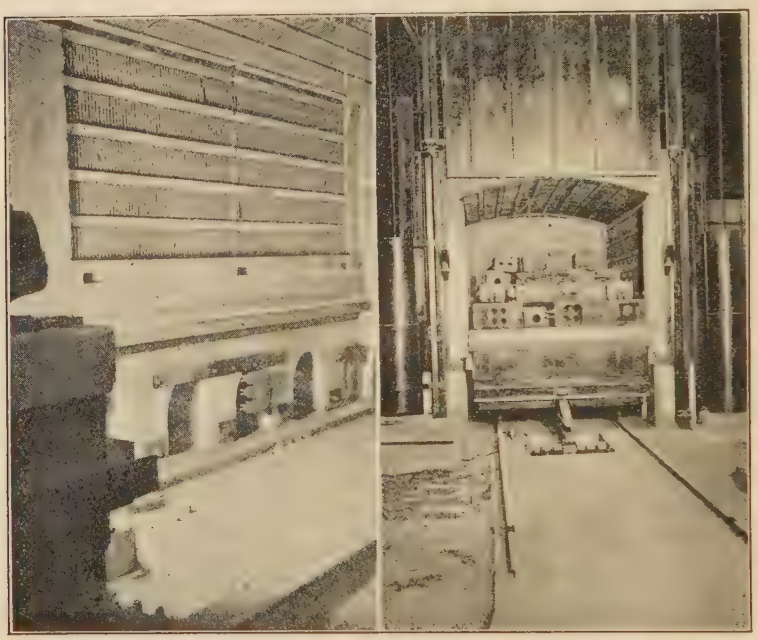
Labor Saving Furnaces.—For heating large pieces and for a large production of similar parts, furnaces with movable or moving hearths mechanically operated have replaced the in-and-out furnace in many plants. Mechanically operated furnaces are more expensive than furnaces with stationary hearths and are not always more economical, and the in-and-out furnace will

continue to function for some time to come. Mechanically operated furnaces are sometimes adopted when other types would be less costly, both in first cost and in operation, because comparison has been made with in-and-out furnaces that have been improperly designed, and for which sufficient working space and

FIG. 99.—Lead bath furnace.

suitable handling equipment has, perhaps, not been provided. A number of in-and-out furnaces will often produce at less cost than one large continuous furnace if production is irregular or intermittent. For a large and regular production, however, with a continued output of similar parts, the mechanically operated furnace produces at a lower cost.

Furnaces with Movable Hearth.—Large and heavy pieces are not easily handled, and the loading and unloading of in-and-out furnaces with such pieces sometimes presents a difficult labor problem. This problem has been solved by the movable hearth that can be removed from the furnace for loading. Such furnaces are of two types, the elevator and the car furnace. The furnace proper of the elevated type is placed well above



(*a*) (*b*)

FIG. 100.—Car type furnace electrically heated. (*Courtesy Electric Heating Apparatus Co.*)

the floor level on supports, the hearth being raised to the furnace or lowered to the floor as desired. This type of furnace is not generally used in heat treatment but is applied to annealing heavy pieces. The car type is used quite extensively for annealing and for carburizing. Figure 100 *B* illustrates a car type of furnace electrically heated. Figure 100 *A* shows the arrangement of the heating elements and the method of sealing. The design of such furnaces follows standard practice, but overfiring is required if either gas or oil is used for heating. Figure 101 shows the design of a car furnace with a separate

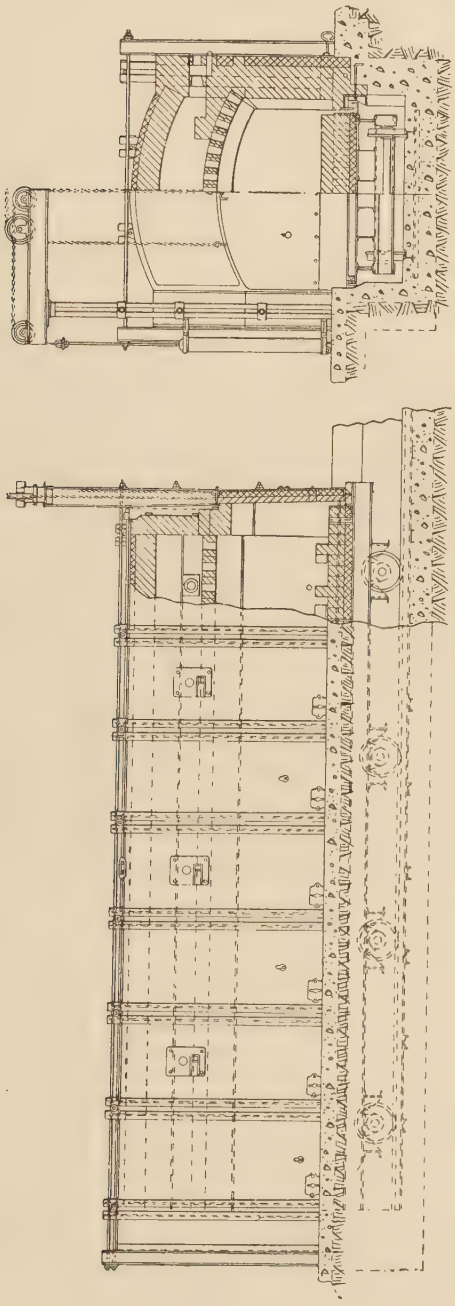


FIG. 101.—Car hearth. (*Courtesy McCann-Harrison Co.*)

combustion chamber placed above the working chamber and heated with oil.

Continuous Furnaces.—Continuous furnaces are primarily intended for the saving of labor, although sometimes required for special purposes, and much ingenuity has been shown in the design of the mechanical equipment. A complete description of continuous furnaces would require a large volume that would probably be out of date as soon as published because of the continued development of new types. Continuous furnaces,

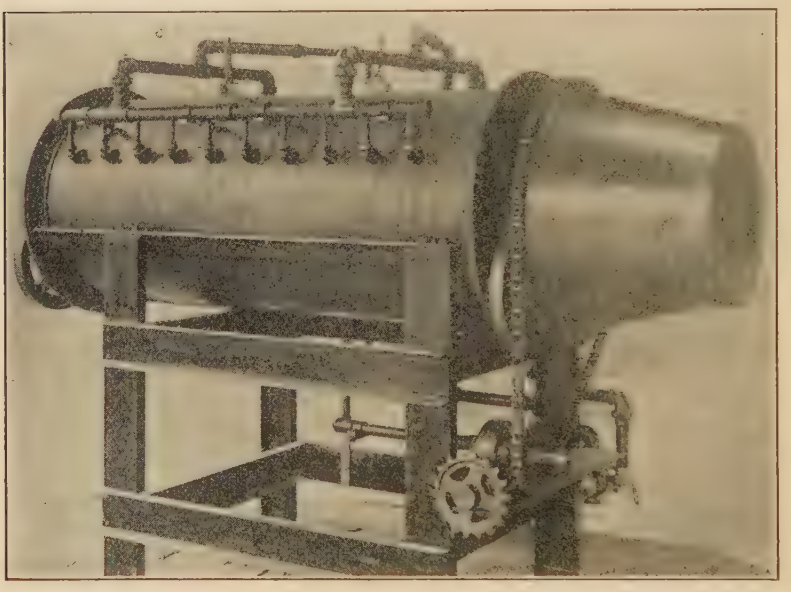


FIG. 102.—Rotary retort heating furnace. (*Courtesy American Gas Furnace Co.*)

however, are of five general types and can be classified accordingly as rotary retort, pusher, walking beam, revolving hearth, and chain or carrier of which there are many kinds. Because of the many combinations of mechanical methods that are possible, a furnace may possibly fall into more than one class.

Rotary-retort Furnaces.—The rotary retort furnace is generally used for heating or carburizing small pieces and is, perhaps, as much a fuel-saving as a labor-saving furnace. Figure 102 shows a rotary-retort heating furnace, gas fired. The number and the placing of the burners should be noted. The photograph of Fig. 103 shows a battery of gas-fired rotary-retort carburizing

furnaces. Such furnaces are coming into more extensive use and are well adapted to the carburizing of parts of moderate size. Gas may be the carburizing agent, but city gas is usually supplemented by carburizing compound, or compound alone may be used.

Rotary-retort furnaces are not properly continuous furnaces. Such furnaces are of four general types—pusher, walking beam, revolving hearth, and conveyor. Conveyor furnaces are also of different types, for example chain, plate, and belt. Such

FIG. 103.—Rotary retort carburizing furnaces. (*Courtesy American Gas Furnace Co.*)

furnaces are intended to save labor in charging and discharging, although furnaces with revolving hearth are sometimes charged by hand, and manual labor may be required to place the charge in the furnace.

Pusher Furnaces.—Pusher furnaces have long been used for heavy work, for example in the heating of billets in rolling mills or in forge shops, and have also been used for heat treatment. The mechanical power is supplied by a hydraulic cylinder, toggle, or other device by which the load is pushed a certain distance, and the space left on the backward stroke is filled by another piece to be heated. Figure 104 shows a pusher furnace

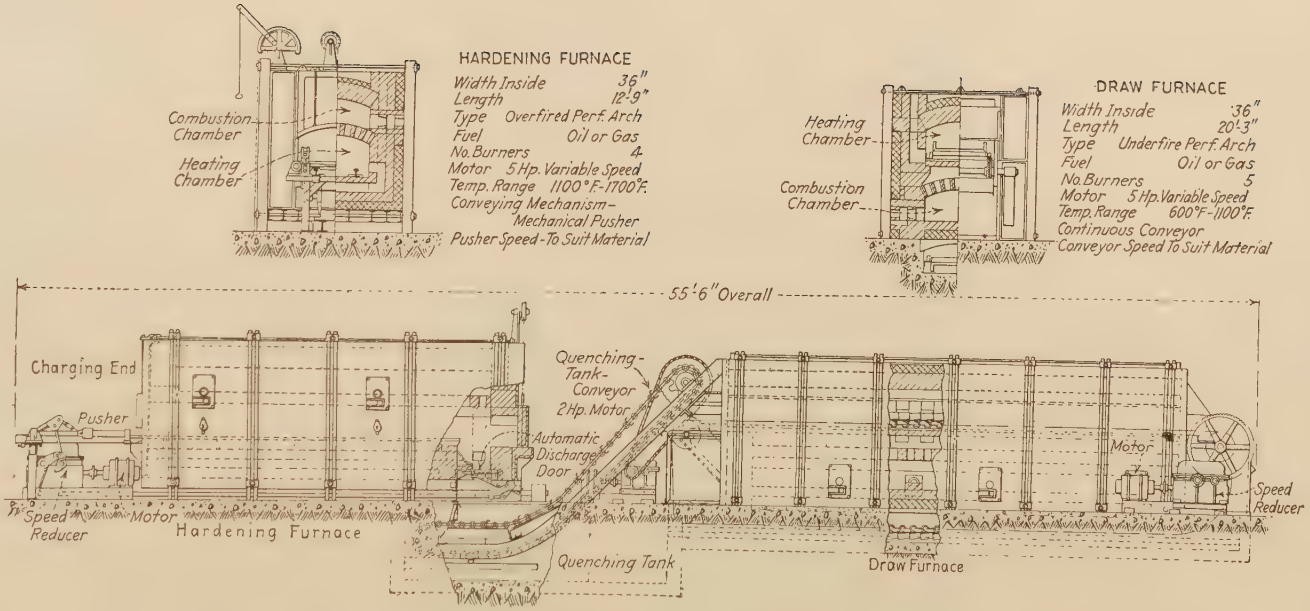


FIG. 104.—Pusher and conveyor furnace.

FIG. 105.—(a) (*Courtesy of McCann-Harrison Co.*)

FIG. 105 (*Continued*).—(*b*) Plate conveyor. (*Courtesy McCann-Harrison Co.*)

for heating before quenching with a quenching tank below the floor at the outlet end. From the quenching tank the charge

FIG. 106.—Pusher furnace. (*Courtesy Surface Combustion Co.*)

FIG. 107.—Pusher.

is carried by conveyor into a drawing furnace, that illustrated being of the chain type. The different methods of firing the

two furnaces are of interest. Figure 105 (*a*) pictures another pushing arrangemnt for the handling of small parts in trays. At the outgoing end (Fig. 105 (*b*)), these trays turn on the trunnions provided and drop the parts into the quenching tank. As illustrated, the trays are returned to the charging end by hoist and monorail. A gas-fired pusher furnace with discharge door at the side is shown in Fig. 106. An unusual type of pushing machine for handling many small parts is shown in Fig. 107.

A furnace of this type is easily emptied by passing unfilled trays through the furnace, but furnaces filled with large pieces such as billets are not so easily emptied, although *blanks* can be used for that purpose. The difficulty of unloading the furnace completely is a disadvantage, but one that is minor. The

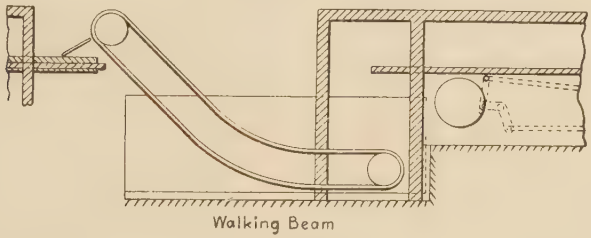


FIG. 108 (*a*).

mechanical equipment required is usually less expensive than that required for continuous furnaces. It is easily repaired or replaced without shutting down the furnace. Rails or beams can be laid on the floor to carry the charge, thus preventing wear of the floor, and they may also replace the floor entirely. No heat units will be wasted in heating brickwork if the floor is replaced by rails or beams. The combustion chamber can be placed below the floor or rails, and electrical heating units can also be so placed.

Walking-beam Furnaces.—The walking-beam furnace is also an early type that has been used for simple heating or for steel treating. Rails or beams move with a circular motion in longitudinal slots in the floor, lifting the charge and moving it forward a short distance until it again rests upon the floor. The beam may be moved by a toggle attached to it or by a revolving arm. The mechanical equipment of a walking-beam furnace is illustrated in the drawing of Fig.

113 and in the simple sketches of Fig. 108, (*a*) and (*b*). The furnace of Fig. 113 has a walking beam in the hardening chamber, below, and a chain conveyor in the drawing chamber, above.

Furnaces with Revolving Hearth.—Furnaces with revolving hearth are not always continuous in that they are charged at one door and discharged at another. Revolving hearths have been used simply to obtain more uniform heating, only one door being provided for charging and discharging. Modern furnaces of this type, however, are continuous and are used for hardening, drawing, and carburizing. Figure 109 shows the cross-section of a furnace with revolving hearth heated by oil or gas. Furnaces of this type are also heated by electricity, and Fig. 110 *A* is a photograph of a hardening and a drawing furnace so heated. The picture also illustrates the conveying

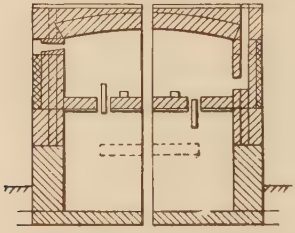


Fig. 108(*b*).

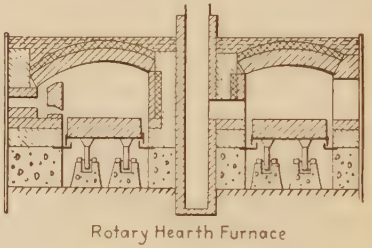


Fig. 109.

system for removing parts from the quenching bath. Figure 110 *B* is another view. Parts are charged into the furnace by a rocker arm, as illustrated, through one door and pushed out, after traveling around the furnace, by a similar rocker arm on the other side only a small part of which is visible. Charging and discharging doors are side by side. Parts are charged into and discharged from the drawing furnace, partly hidden by the conveyor, in the same way. The hearth is moved by a lever and rack.

Conveyor Furnaces.—Chain conveyors for furnaces are almost as numerous in type as furnaces to which they are applied. Link chain, endless belt, chains with special fixtures, and hinged plates are some examples. Figure 111 is a photograph of a furnace with a special conveyor for local hardening, blocks being attached to the chain so to hold parts passing through the furnace that the center will be unhardened because below the hardening temperature on leaving the furnace. The exposed

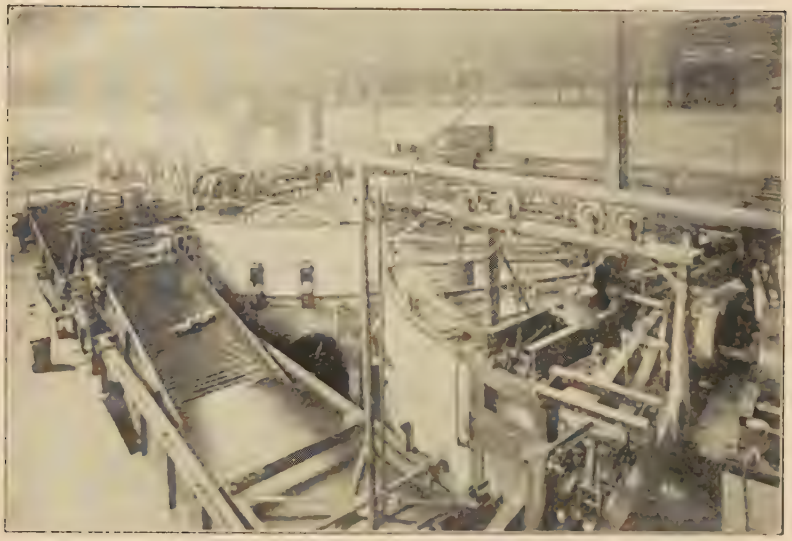


Fig. 110.—(*a*) Rotary hearth electric hardening and drawing furnaces.

Fig. 110 (*Continued*).—(*b*) Electrically heated rotary hearth furnace operated automatically.

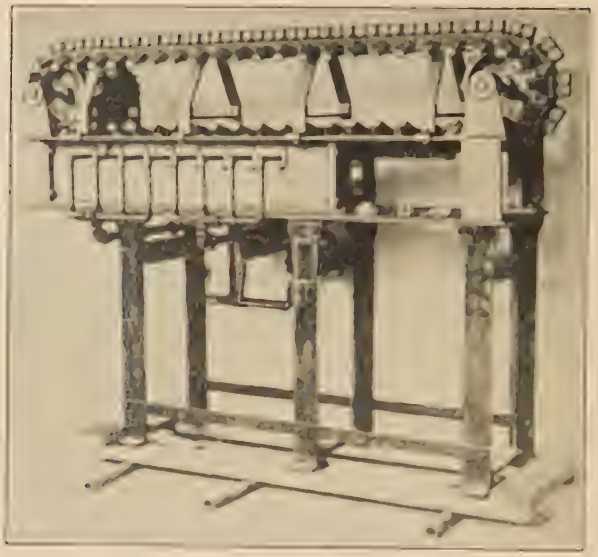


FIG. 111.—Gas-fired furnace for local or selective hardening.

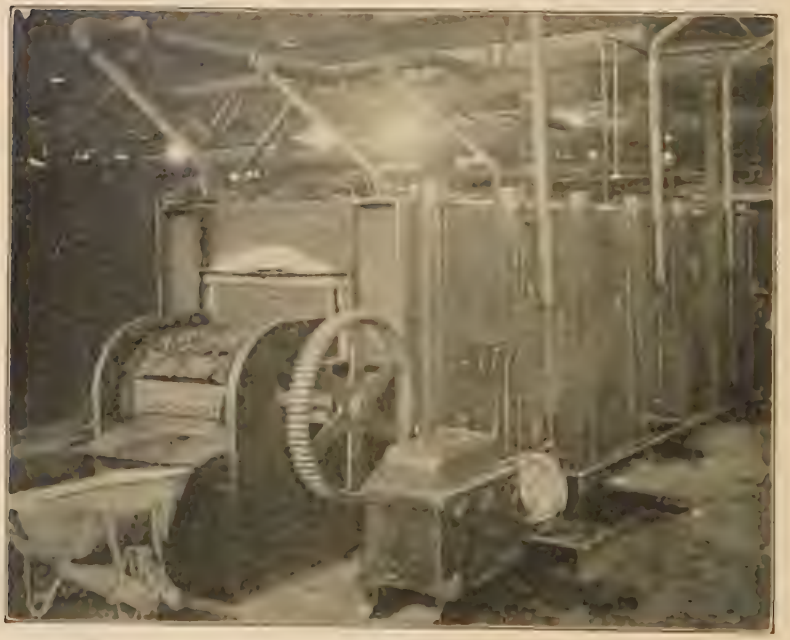


FIG. 112.—Plate conveyor. (*Courtesy McCann Harrison Co.*)

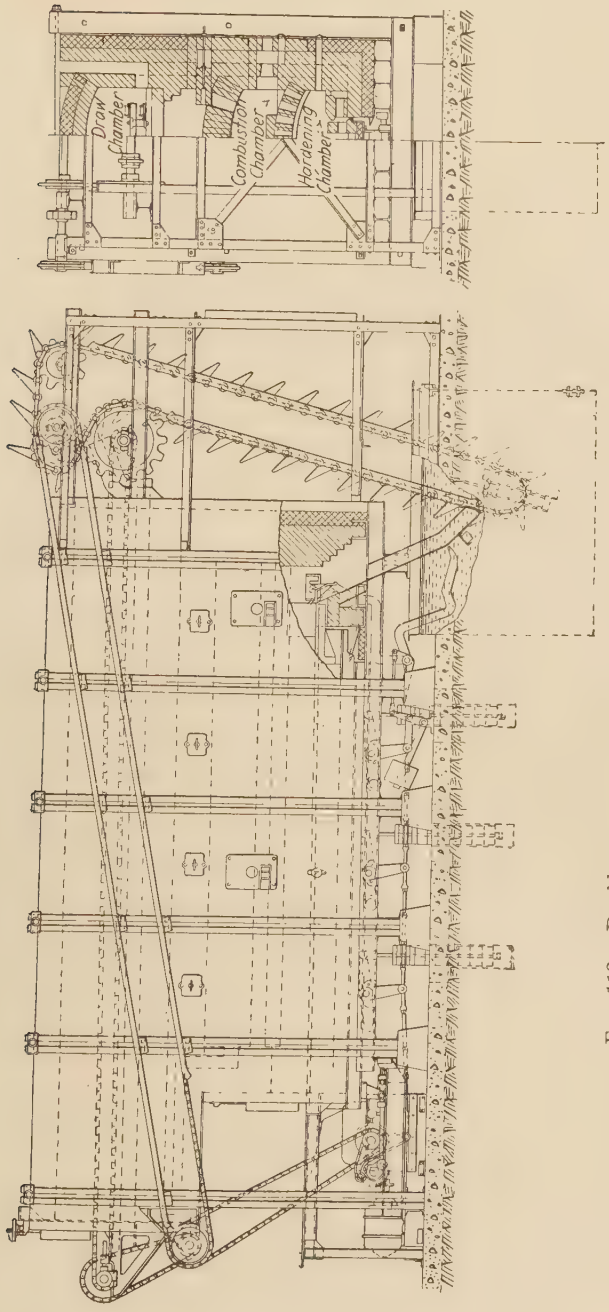


FIG. 113.—Double-purpose automatic furnace. (*Courtesy McCann Harrison Co.*)

portions reach the hardening temperature just before leaving the furnace. Furnaces of similar type are used for hardening the edges only of mower and reaper blades. With such furnaces, automatic feeding devices are usually provided.

Figure 112 pictures the discharge end of a continuous drawing furnace with a conveyor of hinged plates, an unusual type. The simplicity of the final handling is apparent. Because a door would prevent the passage of the parts carried on the

FIG. 114.—(*a*) (*Courtesy McCann Harrison Co.*)

conveyor, the discharge end is equipped with a cover of chain that prevents any great loss of heat without interfering with the passage of parts.

Double-purpose Furnace with Two Hearths.—Figure 113 shows an unusual combination of two chambers in one furnace with a drawing furnace above a hardening furnace and separated by the combustion chamber. For movement through the hardening furnace, a walking beam is provided; and in the drawing furnace, a chain conveyor. Charging and discharging

at the same end of the furnace requires but one operator, as shown in the photographs of Fig. 114 (*a*). The other end of the furnace with the conveyor from the quenching tank to the drawing chamber is illustrated in Fig. 114 (*b*). The drawing chamber is heated by the waste gases from the heating chamber supplemented by direct heating from the combustion chamber if required. Flues pass through the roof of the combustion

FIG. 114 (*Continued*).—(b) Combined hardening and drawing furnace automatic. (*Courtesy McCann Harrison Co.*)

chamber to the drawing chamber and are provided with dampers, as illustrated in Fig. 113, which can be opened when more heat is required for drawing.

A more conventional type of furnaces with chain conveyor is shown in the gas-heated, overfired furnace of Fig. 115; and in Fig. 116, a new type of belt conveyor very convenient for handling small parts.

FIG. 115.—Conveyor furnace. (*Courtesy Surface Combustion Co.*)

FIG. 116.—Belt-conveyor furnace. (*Courtesy Surface Combustion Co.*)

Purposes and Applications of Continuous Furnaces.—Continuous furnaces may be used for purposes other than the saving of labor, for example in local hardening or for more rapid or more uniform heating than is possible in stationary furnaces because of the size or shape of the pieces to be treated, and manual labor may be necessary for handling in quenching and drawing as well as for loading and unloading. Mechanical equipment, however, is intended primarily to save labor and should be applied to all operations as far as is possible, and manual labor limited to the start and finish of the process to be performed, to

FIG. 117.—Hardening and quenching equipment.

bringing parts to the furnace and removing them when the process is completed. With conveyors from the quenching tank to the continuous drawing furnace, or to transfer containers, labor-saving equipment is practically complete. Such equipment can be applied to small production as well as to large production, of which examples have been shown, and in Fig. 117 is shown a convenient arrangement for carburizing and hardening small parts with a rotary-retort carburizing furnace, a continuous furnace, and a quenching tank equipped with conveyor for unloading. The furnaces illustrated are heated by gas.

The continuous furnace cannot replace the in-and-out furnace for all production, because the cost will often be higher in spite

of the labor-saving equipment. The stationary furnace is well adapted to processes that require holding at temperature for a long time or for heavy loads that require time to reach the temperature desired. Continuous furnaces can be designed for such processes, but frequently labor is not saved. By proper planning, a small crew can handle a large number of in-and-out furnaces in which a charge remains for several hours. Mechanical equipment for transfer to and from the furnaces and from the quenching tanks will aid stationary-furnace practice. Chain and belt conveyor, tongs, hoists, monorails, and other handling equipment will save much labor. Equipment can also be supplied for loading and unloading, for example the *tier lift* electric truck provided with a projecting platform that can be raised and lowered so that a load can be lifted from the floor and placed within the heating chamber of the furnace.

Thermal Efficiency.—The thermal efficiency of a furnace can be calculated mathematically, but such calculation is not necessary in stating the principles upon which efficiency is based. The heat units applied to raising the temperature of the charge to the point required are utilized, the rest is wasted. Because it is also necessary to raise the temperature of the furnace, the heat units so required may be included in the heat units utilized. The efficiency will be the ratio between the heat units utilized and the total applied. Increasing efficiency is a matter of reducing heat losses, and methods of construction for reducing heat losses have been described. Heat leaves an in-and-out furnace in the gases that leave the furnace and in the charge that is heated. In continuous furnaces, heat may also be lost in the conveyor. A chain or carrier that passes through the furnace, into the air, and back to the furnace carries off a large number of heat units. No heat is lost through the conveying equipment in pusher, revolving-hearth, walking-beam, and rotary-retort furnaces, an advantage over the chain type of furnace. To conserve heat, chains should be no larger than necessary to carry the load.

Thermal efficiency does not always mean operating efficiency. Rapid transfer of heat even with a low thermal efficiency may reduce the cost of producing by increasing the output beyond that obtained with slower heating and higher thermal efficiency. The thermal efficiency of a continuous furnace is usually lower than that of the stationary furnace, but the operating efficiency will usually be much higher. This, however, does not mean

that heat must necessarily be thrown away in operating a continuous furnace but rather that the waste heat be reduced as far as possible. The furnace of Fig. 113 has been so designed.

The heat required by a charge is lost when a furnace is unloaded. Ordinarily, this loss is not taken into account in determining the thermal efficiency of a furnace, because the principal object is the heating of the charge. If heating is followed by quenching, the stored heat is completely lost. If, however, the charge is to be cooled in air, some of the heat units in the outgoing charge can be used to heat the incoming charge by means of a counterflow. Counterflow furnaces are of two

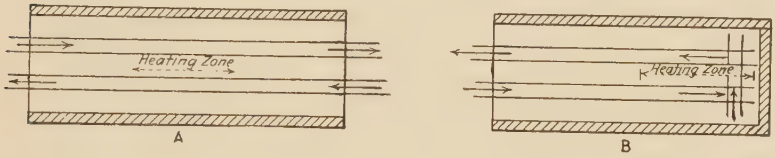


FIG. 118.—Methods of counterflow.

types. In one, the charge passes through the furnace in two parallel rows moving in opposite directions, as illustrated in the sketch, Fig. 118 A. To avoid the loss of heat from two doors and to shorten the length required for a given charge, the charge is loaded and unloaded at the same door, as in the sketch of Fig. 118 B. The charge moves along one side of the furnace to the back wall and is then transferred mechanically to the opposite side and is carried to the door by a conveyor. The counterflow furnace was developed for economical heating by electricity and is used particularly for carburizing. If carburized parts are quenched direct, however, the counterflow furnace cannot be used.

CHAPTER XIII

PYROMETERS

Temperature Control. Indirect Methods.—The heat treatment of steel, being based upon definite temperatures or critical points, requires some means of determining temperature that will at least tell when the desired temperature has been reached. Temperatures are now determined directly by pyrometer, but not so long ago pyrometers did not exist, and temperatures were determined by indirect methods. The wet finger is still serviceable in determining the proper heating of a flatiron, and similar methods are useful in determining the temperature of steel in the lower range. In the higher range, heating colors, the appearance of the fracture after hardening, and other natural phenomena serve to indicate temperature indirectly—methods once a necessity because no others were available and still used, often with surprising accuracy. The magnet, indicating the temperature at which steel loses or regains magnetism, is still in service. Such methods are sometimes more accurate than the pyrometer because applied directly to the steel being heated.

Heating Colors.—Heating colors are probably the oldest standards for hardening temperatures and as old as the heat treatment of steel. When heated to about 900° F. (480° C.), steel begins to give off light, first a deep red just visible in darkness and changing to lighter shades of red, then to yellow and white as the temperature rises. The shades of color in the hardening range are so distinctive that an experienced hardener can sometimes control temperature within 15 to 20° F. (about 10° C.) by color. Directions for hardening still advise "harden at a cherry red." These colors, however, appear brighter in darkness than in daylight, so that even a skilled operator can make mistakes if lighting conditions change. To provide a reasonably constant standard of light, hardening rooms were often placed in dark corners and had few or no windows, and heat treatment was not a pleasant occupation in hot weather.

Fracture Test.—The hardening of high-carbon steel by heating colors can be checked by the appearance of the fracture. Pieces quenched at temperatures below the hardening point will not be sufficiently hard, and if heated too hot, the fracture will be of coarse grain; properly hardened, will appear silky. Increase of grain size with temperature is gradual, and a skilled hardener can tell the hardening temperature within 20 or 30° F. (10 or 15° C.) by the appearance of the fracture. The fracture test is convenient for temperature control when a pyrometer is not available and is sometimes a useful check on the pyrometer. For this, small test pieces of high-carbon steel or carburized pieces can be used. This method is serviceable in checking the operation of a continuous furnace operated at temperatures considerably above the hardening temperature.

Drawing Colors.—Such methods can be applied to hardening or annealing, but not to drawing at temperatures below red heat or below the hardening point. For drawing, however, nature has provided a series of surface colors that correspond closely to temperature under constant conditions for temperatures up to about 500° F. (260° C.). The drawing colors have been described in connection with tool hardening. These colors are supplemented by other tests of a rough-and-ready character, of which the wet finger and the scorching of wood are examples.

Mixtures of Known Melting Point.—More accurate knowledge of temperature within a furnace can be obtained by introducing mixtures of known melting point, a method not much used in heat treatment because of the other methods of temperature control available, but one that has been serviceable in the ceramics industry and others. Mixtures with melting points within the working range of temperature are provided—usually, one with a melting point just below the desired temperature; one melting close to that point; and a third with a melting point somewhat higher. Such mixtures are commonly supplied in the form of a cone, so that the start of melting can be observed quickly. This and other indirect methods of temperature control have been supplanted by the pyrometer that measures temperature directly, as does the thermometer, and for a much greater range of temperature.

Direct Measurement of Temperature. Resistance and Thermocouple Pyrometer.—Direct-reading pyrometers are of two types, and both are electrical instruments that measure the change

of electrical properties with change of temperature. Knowing the properties that correspond with given temperatures, the measuring instruments can be calibrated in terms of temperature. One type of pyrometer, the resistance pyrometer, measures the resistance of a bulb of platinum wire and the change of resistance with change of temperature. The bulb consists of fine platinum wire wound on a core of mica and protected by a tube porcelain and an outer tube of nickel. Tubes and contents constitute the *fire end* from which connection is made to the measuring instrument. The resistance pyrometer is easily checked by measuring the resistance at room temperature, a pail of water at constant temperature being all that is required, but the instrument is costly and delicate. For heat-treatment purposes, the other type of pyrometer, the thermocouple pyrometer, is preferred because less expensive and more rugged.

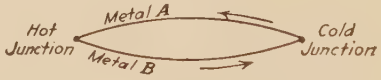


Fig. 119.—Principle of thermocouple.

Principle of Thermocouple.—The industrial thermocouple consists of two wires of dissimilar metals welded at one end, called the "hot junction," and connected from the other end called the "cold junction," by lead wires to a measuring instrument. If the hot junction is heated and the circuit closed, a current will flow, as in Fig. 119, the strength depending upon the difference in temperature of the hot and cold junctions. The voltage developed is small, and the measuring instrument is, therefore, calibrated in millivolts—thousandths of a volt. As this voltage is proportional to temperature, the measuring instrument can be calibrated for temperature as well as for millivolts but for only one type of couple, each type differing in the millivoltage produced on heating. Any two dissimilar metals will form a thermocouple, but only four combinations are employed in industrial practice, and of these three only are suitable for heat-treatment purposes in that they will stand up at high temperature and supply a continuously and regularly increasing electromotive force with increase of temperature, an e. m. f. sufficiently large for reasonably accurate measurement. These three couples are known, respectively, as "platinum, platinum-rhodium," "iron-constantan," and "chromel—alumel."

The fourth, copper—constantan, is not suitable for the conventional temperatures of heat treating but is well adapted to low temperature and develops a comparatively large e. m. f. The tables show the e. m. f. developed by these couples when heated.

Platinum, Platinum-rhodium Thermocouple.—The platinum, platinum-rhodium couple consists of a wire of platinum and a wire of an alloy of 90 per cent platinum and 10 per cent rhodium. This is the first couple to be applied to measuring temperatures for heat treating. This couple is expensive but can be used at much higher temperatures than the others with, perhaps, 2750° F. (1510° C.) as a maximum. Platinum being costly, the size of the wire employed is comparatively small. Platinum, platinum-rhodium couples are usually slightly more accurate than other couples, although more easily contaminated. Because of the high cost, this couple has been replaced in industrial practice by the iron—constantan or chromel—alumel, the so-called "base-metal couples."

Iron-Constantan Thermocouple.—The iron-constantan couple consists of one wire of iron and one of constantan, an alloy containing approximately 54 per cent of copper and 44 per cent of nickel with other elements in small amount. This couple is satisfactory for temperatures up to about 1800° F. (980° C.) and develops a much greater e. m. f. than platinum, platinum-rhodium. Both iron and constantan are easily oxidized, however, and must be well protected. Iron-constantan is still in service, but for heat treating preference is now given to the third couple, chromel-alumel.

Chromel-Alumel Thermocouple.—Chromel, or nichrome, is an alloy containing approximately 90 per cent of nickel and 10 per cent of chromium; alumel contains approximately 94 per cent of nickel, 1 per cent of silicon, 2 of aluminum, and 3 of manganese. The chromel-alumel couple is highly resistant to oxidation and can be used at higher temperatures than iron—constantan. The maximum temperature for chromel-alumel is usually presumed to be about 2100° F. (1150° C.), but this couple can be used at temperatures as high as 2400° F. (1315° C.) if the wire is of large size. The metal is quickly oxidized with the formation of a thin, hard, protective scale that is an insulator against current leaks. Chromel-alumel couples deteriorate in a reducing atmosphere and require protection against the furnace gas, but merely a tube open at one end is all that is

PLATINUM 1—PLATINUM PLUS 10 PER CENT RHODIUM THERMOCOUPLE, COLD JUNCTION 0° F., MILLIVOLTS

Degrees Fahrenheit...	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400
0	0	0.321	0.694	1.11	1.57	2.05	2.55	3.07	3.60	4.14	4.69	5.25	5.82	6.41	7.00
5	0.016	0.339	0.715	1.13	1.59	2.07	2.58	3.10	3.63	4.17	4.72	5.28	5.85	6.44	7.03
10	0.032	0.358	0.736	1.16	1.62	2.10	2.60	3.12	3.65	4.19	4.75	5.31	5.88	6.47	7.06
15	0.048	0.377	0.757	1.18	1.64	2.12	2.63	3.15	3.68	4.22	4.77	5.34	5.91	6.50	7.09
20	0.064	0.396	0.778	1.20	1.67	2.15	2.65	3.18	3.71	4.25	4.80	5.36	5.94	6.53	7.12
25	0.080	0.414	0.799	1.22	1.69	2.17	2.68	3.20	3.74	4.28	4.83	5.39	5.97	6.56	7.15
30	0.096	0.433	0.820	1.25	1.71	2.20	2.71	3.23	3.76	4.31	4.86	5.42	6.00	6.59	7.18
35	0.112	0.452	0.841	1.27	1.74	2.22	2.73	3.26	3.79	4.33	4.89	5.45	6.03	6.62	7.21
40	0.128	0.470	0.862	1.29	1.76	2.25	2.76	3.28	3.82	4.36	4.91	5.48	6.06	6.65	7.24
45	0.144	0.489	0.883	1.32	1.79	2.27	2.78	3.31	3.84	4.39	4.94	5.51	6.09	6.68	7.27
50	0.160	0.508	0.904	1.34	1.81	2.30	2.81	3.34	3.87	4.41	4.97	5.54	6.12	6.71	7.30
55	0.176	0.526	0.925	1.36	1.84	2.32	2.84	3.36	3.90	4.44	5.00	5.56	6.14	6.73	7.33
60	0.192	0.545	0.946	1.39	1.86	2.35	2.86	3.39	3.92	4.47	5.03	5.59	6.17	6.76	7.36
65	0.208	0.563	0.967	1.41	1.88	2.37	2.89	3.41	3.95	4.50	5.05	5.62	6.20	6.79	7.39
70	0.224	0.582	0.988	1.43	1.91	2.40	2.91	3.44	3.98	4.52	5.08	5.65	6.23	6.82	7.42
75	0.240	0.600	1.01	1.46	1.93	2.42	2.94	3.47	4.00	4.55	5.11	5.68	6.26	6.85	7.45
80	0.256	0.619	1.03	1.48	1.95	2.45	2.97	3.49	4.03	4.58	5.14	5.71	6.29	6.88	7.48
85	0.273	0.638	1.05	1.50	1.98	2.47	2.99	3.52	4.06	4.61	5.17	5.73	6.32	6.91	7.51
90	0.289	0.657	1.07	1.52	2.00	2.50	3.02	3.55	4.09	4.63	5.19	5.76	6.35	6.94	7.54
95	0.305	0.675	1.09	1.55	2.03	2.52	3.04	3.57	4.11	4.66	5.22	5.79	6.38	6.97	7.57
100	0.321	0.694	1.11	1.57	2.05	2.55	3.07	3.60	4.14	4.69	5.25	5.82	6.41	7.00	7.60
Millivolts per degree.	0.0032	0.0037	0.0042	0.0046	0.0048	0.0050	0.0062	0.0053	0.0054	0.0055	0.0056	0.0057	0.0059	0.0059	0.0060

Degrees Fahrenheit...	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400	2500	2600	2700	2800	2900
0	7.60	8.21	8.83	9.46	10.10	10.76	11.42	12.08	12.75	13.41	14.08	14.76	15.43	16.10	16.77
5	7.63	8.24	8.86	9.49	10.13	10.79	11.45	12.11	12.78	13.44	14.11	14.79	15.46	16.13	16.80
10	7.66	8.27	8.89	9.52	10.17	10.83	11.49	12.15	12.82	13.48	14.15	14.83	15.50	16.17	16.84
15	7.69	8.30	8.92	9.56	10.20	10.86	11.52	12.18	12.85	13.51	14.18	14.86	15.53	16.20	16.87
20	7.72	8.33	8.96	9.59	10.23	10.89	11.55	12.21	12.88	13.54	14.22	14.89	15.56	16.23	16.90
25	7.75	8.36	8.99	9.62	10.26	10.92	11.58	12.25	12.91	13.58	14.25	14.93	15.60	16.27	16.93
30	7.78	8.40	9.02	9.65	10.30	10.96	11.62	12.28	12.95	13.61	14.28	14.96	15.63	16.30	16.97
35	7.81	8.43	9.05	9.68	10.33	10.99	11.65	12.31	12.98	13.64	14.32	14.99	15.66	16.33	17.00
40	7.84	8.46	9.07	9.72	10.36	11.02	11.68	12.35	13.01	13.68	14.36	15.03	15.70	16.37	17.03
45	7.87	8.49	9.11	9.75	10.40	11.06	11.72	12.38	13.05	13.71	14.39	15.06	15.73	16.40	17.07
50	7.90	8.52	9.14	9.78	10.43	11.09	11.75	12.42	13.08	13.75	14.42	15.10	15.77	16.44	17.10
55	7.94	8.55	9.18	9.81	10.46	11.12	11.78	12.45	13.11	13.78	14.45	15.13	15.80	16.47	17.13
60	7.97	8.58	9.21	9.84	10.50	11.16	11.82	12.48	13.15	13.81	14.49	15.16	15.83	16.50	17.17
65	8.00	8.61	9.24	9.88	10.53	11.19	11.85	12.52	13.18	13.85	14.52	15.20	15.87	16.54	17.20
70	8.03	8.64	9.27	9.91	10.56	11.22	11.88	12.55	13.21	13.88	14.56	15.23	15.90	16.57	17.23
75	8.06	8.67	9.30	9.94	10.60	11.26	11.92	12.58	13.25	13.91	14.59	15.26	15.93	16.60	17.27
80	8.09	8.71	9.33	9.97	10.63	11.29	11.95	12.62	13.28	13.95	14.62	15.30	15.97	16.64	17.30
85	8.12	8.74	9.37	10.00	10.66	11.32	11.98	12.65	13.31	13.98	14.66	15.33	16.00	16.67	17.33
90	8.15	8.77	9.40	10.04	10.69	11.35	12.01	12 68	13.34	14.01	14.69	15.36	16.03	16.70	17.36
95	8.18	8.80	9.43	10.07	10.73	11.39	12.05	12.72	13.38	14.05	14.73	15.40	16.07	16.74	17.40
100	8.21	8.83	9.46	10.10	10.76	11.42	12.08	12.75	13.41	14.08	14.76	15.43	16.10	16.77	17.43
Millivolts per degree.	0.0061	0.0062	0.0063	0.0064	0.0066	0.0066	0.0066	0.0067	0.0066	0.0067	0.0068	0.0067	0.0067	0.0067	0.0066

IRON-CONSTANTAN THERMOCOUPLE WITH COLD JUNCTION AT 0° F. MILLIVOLTS

Degrees Fahrenheit.....	0	100	200	300	400	500	600	700	800	900	1000
0	0	2.88	5.84	8.87	11.94	15.01	18.08	21.15	24.23	27.33	30.46
5	0.144	3.03	5.99	9.02	12.10	15.16	18.23	21.30	24.38	27.49	30.62
10	0.288	3.18	6.14	9.18	12.24	15.32	18.39	21.46	24.54	27.64	30.78
15	0.432	3.32	6.29	9.33	12.40	15.47	18.54	21.61	24.69	27.80	30.94
20	0.576	3.47	6.45	9.48	12.55	15.62	18.69	21.77	24.85	27.96	31.10
25	0.720	3.62	6.60	9.64	12.71	15.78	18.85	21.92	25.00	28.11	31.26
30	0.864	3.77	6.75	9.79	12.86	15.93	19.00	22.07	25.16	28.27	31.42
35	1.01	3.92	6.90	9.94	13.01	16.08	19.15	22.23	25.31	28.42	31.58
40	1.15	4.06	7.05	10.10	13.17	16.24	19.31	22.38	25.47	28.58	31.74
45	1.30	4.21	7.20	10.25	13.32	16.39	19.46	22.54	25.62	28.74	31.90
50	1.44	4.36	7.36	10.40	13.47	16.54	19.61	22.69	25.78	28.89	32.06
55	1.58	4.51	7.50	10.56	13.63	16.70	19.77	22.84	25.93	29.05	32.22
60	1.73	4.66	7.66	10.71	13.78	16.85	19.92	23.00	26.09	29.21	32.38
65	1.87	4.80	7.81	10.86	13.94	17.00	20.07	23.15	26.24	29.36	32.54
70	2.02	4.95	7.96	11.02	14.09	17.16	20.23	23.31	26.40	29.52	32.70
75	2.16	5.10	8.11	11.17	14.24	17.31	20.38	23.46	26.55	29.68	32.86
80	2.30	5.25	8.26	11.32	14.40	17.47	20.54	23.61	26.71	29.83	33.02
85	2.45	5.40	8.42	11.47	14.55	17.62	20.69	23.77	26.86	29.99	33.18
90	2.59	5.54	8.57	11.63	14.70	17.77	20.84	23.92	27.02	30.15	33.34
95	2.74	5.69	8.72	11.78	14.86	17.93	21.00	24.08	27.17	30.30	33.50
100	2.88	5.84	8.87	11.94	15.01	18.08	21.15	24.23	27.33	30.46	33.66
Millivolts per degrees Fahrenheit.....	0.0288	0.0296	0.0303	0.0307	0.0307	0.0307	0.0307	0.0308	0.0310	0.0313	0.0320

Degrees Fahrenheit	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100
0	33.66	36.96	40.38	43.88	47.40	50.92	54.44	57.96	61.48	65.00	68.52
5	33.82	37.13	40.56	44.06	47.58	51.10	54.62	58.14	61.66	65.18	68.70
10	33.99	37.30	40.73	44.23	47.75	51.27	54.79	58.31	61.83	65.35	68.87
15	34.15	37.47	40.90	44.41	47.93	51.45	54.97	58.49	62.01	65.53	69.05
20	34.32	37.64	41.08	44.58	48.10	51.62	55.14	58.66	62.18	65.70	69.22
25	34.48	37.81	41.26	44.76	48.28	51.80	55.32	58.84	62.36	65.88	69.40
30	34.65	37.99	41.43	44.94	48.46	51.98	55.50	59.02	62.54	66.06	69.58
35	34.81	38.16	41.60	45.11	48.63	52.15	55.67	59.19	62.71	66.23	69.75
40	34.98	38.33	41.78	45.29	48.81	52.33	55.85	59.37	62.89	66.41	69.93
45	35.14	38.50	41.95	45.46	48.98	52.50	56.02	59.54	63.06	66.58	70.10
50	35.31	38.67	42.13	45.64	49.16	52.68	56.20	59.72	63.24	66.76	70.28
55	35.47	38.84	42.30	45.82	49.34	52.86	56.38	59.90	63.42	66.94	70.46
60	35.64	39.01	42.48	45.99	49.51	53.03	56.55	60.07	63.59	67.11	70.63
65	35.80	39.18	42.65	46.17	49.69	53.21	56.73	60.25	63.77	67.29	70.81
70	35.97	39.35	42.83	46.34	49.86	53.38	56.90	60.42	63.94	67.46	70.98
75	36.13	39.52	43.00	46.52	50.04	53.56	57.08	60.60	64.12	67.64	71.16
80	36.30	39.70	43.18	46.70	50.22	53.74	57.26	60.78	64.30	67.82	71 34
85	36.46	39.87	43.35	46.87	50.39	53.91	57.43	60.95	64.47	67.99	71.51
90	36.63	40.04	43.53	47.05	50.57	54.09	57.61	61.13	64.65	68.17	71.69
95	36.79	40.21	43.70	47.22	50.74	54.26	57.78	61.30	64.82	68.34	71.86
100	36.96	40.38	43.88	47.40	50.92	54.44	57.96	61.48	65.00	68.52	72.04
Millivolts per degrees Fahrenheit	0.033	0.0342	0.0350	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352	0.0352

FAHRENHEIT TABLE FOR CHROMEL-ALUMEL THERMOCOUPLE WITH COLD JUNCTION AT 0° F., MILLIVOLTS

Degrees Fahrenheit.....	0	100	200	300	400	500	600	700	800	900	1000	1100	1200
0	0	2.16	4.56	6.88	9.11	11.38	13.66	15.91	18.26	20.66	22.96	25.36	27.66
5	0.102	2.28	4.67	6.99	9.22	11.49	13.77	16.02	18.38	20.77	23.08	25.47	27.77
10	0.205	2.40	4.79	7.10	9.34	11.61	13.88	16.14	18.50	20.89	23.20	25.59	27.89
15	0.307	2.52	4.90	7.21	9.45	11.72	13.99	16.26	18.62	21.00	23.32	25.70	28.00
20	0.410	2.64	5.02	7.32	9.57	11.84	14.11	16.38	18.74	21.12	23.44	25.82	28.12
25	0.512	2.76	5.13	7.43	9.68	11.95	14.22	16.50	18.86	21.23	23.56	25.93	28.23
30	0.615	2.88	5.25	7.55	9.79	12.06	14.33	16.61	18.98	21.35	23.68	26.05	28.35
35	0.717	3.00	5.37	7.66	9.90	12.17	14.44	16.73	19.10	21.46	23.80	26.16	28.46
40	0.820	3.12	5.49	7.78	10.02	12.29	14.56	16.85	19.22	21.58	23.92	26.28	28.58
45	0.935	3.24	5.60	7.89	10.13	12.40	14.67	16.96	19.34	21.69	24.04	26.39	28.69
50	1.05	3.36	5.72	8.01	10.25	12.52	14.79	17.08	19.46	21.81	24.16	26.51	28.81
55	1.16	3.48	5.83	8.12	10.36	12.63	14.90	17.20	19.58	21.92	24.28	26.62	28.92
60	1.28	3.60	5.95	8.23	10.47	12.75	15.01	17.32	19.70	22.04	24.40	26.74	29.04
65	1.38	3.72	6.06	8.34	10.58	12.86	15.12	17.43	19.82	22.15	24.52	26.85	29.15
70	1.47	3.84	6.18	8.45	10.70	12.98	15.23	17.55	19.94	22.27	24.64	26.97	29.27
75	1.57	3.96	6.29	8.56	10.81	13.09	15.34	17.67	20.06	22.38	24.76	27.08	29.38
80	1.68	4.08	6.41	8.67	10.93	13.21	15.45	17.79	20.18	22.50	24.88	27.20	29.50
85	1.79	4.20	6.52	8.78	11.04	13.32	15.56	17.90	20.30	22.61	25.00	27.31	29.61
90	1.91	4.32	6.64	8.89	11.16	13.44	15.68	18.02	20.42	22.73	25.12	27.43	29.73
95	2.03	4.44	6.76	9.00	11.27	13.55	15.79	18.14	20.54	22.84	25.24	27.54	29.84
100	2.16	4.56	6.88	9.11	11.38	13.66	15.91	18.26	20.66	22.96	25.36	27.66	29.96
Millivolts per degrees Fahrenheit.....	0.0216	0.024	0.0232	0.0223	0.0227	0.0228	0.0225	0.0235	0.240	0.0230	0.0240	0.0230	0.0230

Degrees Fahrenheit	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400
0	29.96	32.26	34.56	36.86	39.11	41.26	43.36	45.46	47.56	49.66	51.72	53.71
5	30.07	32.37	34.67	36.97	39.22	41.36	43.46	45.56	47.66	49.76	51.82	53.81
10	30.19	32.49	34.79	37.08	39.32	41.47	43.57	45.67	47.77	49.87	51.92	53.91
15	30.30	32.60	34.90	37.19	39.43	41.57	43 67	45.77	47.87	49.97	52.02	54.01
20	30.42	32.72	35.02	37.31	39.54	41.68	43.78	45.88	47.98	50.07	52.12	54.12
25	30.53	32.83	35.13	37.42	39.65	41.78	43.88	45.98	48.08	50.17	52.22	54.22
30	30.65	32.95	35.25	37.53	39.75	41.89	43.99	46.09	48.19	50.28	52.31	54.32
35	30.76	33.06	35.36	37.64	39.86	41.99	44.09	46.19	48.29	50.38	52.41	54.42
40	30.88	33.18	35.48	37.76	39.97	42.10	44.20	46.30	48.40	50.48	52.51	54.53
45	30.99	33.29	35.59	37.87	40.08	42.20	44.30	46.40	48.50	50.58	52.61	54.63
50	31.11	33.41	35.71	37.98	40.18	42.31	44.41	46.51	48.61	50.69	52.71	54.73
55	31.22	33.52	35.82	38.09	40.29	42.41	44.51	46.61	48.71	50.79	52.81	54.83
60	31.34	33.64	35.94	38.21	40.40	42.52	44.62	46.72	48.82	50.89	52.91	54.94
65	31.45	33.75	36.05	38.32	40.51	42.62	44.72	46.82	48.92	51.00	53.01	55.04
70	31.57	33.87	36.17	38.43	40.61	42.73	44.83	46.93	49.03	51.10	53.11	55.14
75	31.68	33.98	36.28	38.54	40.72	42.83	44.93	47.03	49.13	41.20	53.21	55.24
80	31.80	34.10	36.40	38.66	40.83	42.94	45.04	47.14	49.24	51.30	53.31	55.34
85	31.91	34.21	36.51	38.77	40.94	43.04	45.14	47.24	49.34	51.41	53.41	55.44
90	32.03	34.33	36.63	38.88	41.04	43.15	45.25	47.35	49.45	51.51	53.51	55.54
95	32.14	34.44	36.74	38.99	41.15	43.25	45.35	47.45	49.55	51.61	53.61	55.64
100	32.26	34.56	36.86	39.11	41.26	43.36	45.46	47.56	49.66	51.72	53.71	55.74
Millivolts per degrees Fahrenheit	0.0230	0.0230	0.0230	0.0225	0.0215	0.0210	0.0210	0.0210	0.0210	0.0206	0.0199	0.0203

Fahrenheit Table for Copper-constantan Thermocouple with Cold Junction at 0° F.

Degrees Fahrenheit.....	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190
0	0	0.22	0.44	0.66	0.88	1.11	1.33	1.56	1.78	2.01	2.23	2.46	2.69	2.93	3.16	3.40	3.64	3.89	4.14	4.40
2	0.04	0.26	0.48	0.71	0.93	1.15	1.38	1.60	1.83	2.05	2.28	2.51	2.74	2.97	3.21	3.45	3.69	3.94	4.19	4.45
4	0.09	0.31	0.53	0.75	0.97	1.20	1.42	1.65	1.87	2.10	2.32	2.55	2.78	3.02	3.26	3.50	3.74	3.99	4.24	4.50
6	0.13	0.35	0.57	0.79	1.02	1.24	1.47	1.69	1.92	2.14	2.37	2.60	2.83	3.07	3.30	3.54	3.79	4.04	4.29	4.55
8	0.18	0.40	0.62	0.84	1.06	1.29	1.51	1.74	1.96	2.19	2.41	2.64	2.88	3.11	3.35	3.59	3.84	4.09	4.34	4.60
10	0.22	0.44	0.66	0.88	1.11	1.33	1.56	1.78	2.01	2.23	2.46	2.69	2.93	3.16	3.40	3.64	3.89	4.14	4.40	4.65

Degrees Fahrenheit.....	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350	360	370	380	390
0	4.65	4.91	5.16	5.42	5.67	5.93	6.18	6.44	6.70	6.97	7.23	7.50	7.77	8.05	8.32	8.60	8.87	9.15	9.43	9.71
2	4.70	4.96	5.21	5.47	5.72	5.98	6.23	6.49	6.75	7.02	7.28	7.55	7.83	8.11	8.38	8.65	8.93	9.21	9.49	9.77
4	4.75	5.01	5.26	5.52	5.77	6.03	6.28	6.54	6.81	7.07	7.34	7.61	7.88	8.16	8.43	8.71	8.98	9.26	9.54	9.82
6	4.80	5.06	5.31	5.57	5.82	6.08	6.34	6.60	6.86	7.12	7.39	7.66	7.94	8.21	8.49	8.76	9.04	9.32	9.60	9.88
8	4.85	5.11	5.36	5.62	5.87	6.13	6.39	6.65	6.91	7.18	7.45	7.72	7.99	8.27	8.54	8.82	9.09	9.37	9.65	9.93
10	4.91	5.16	5.42	5.67	5.93	6.18	6.44	6.70	6.97	7.23	7.50	7.77	8.05	8.32	8.60	8.87	9.15	9.43	9.71	9.99

Degrees Fahrenheit.....	400	410	420	430	440	450	460	470	480	490	500	510	520	530	540	550	560	570	580	590
0	9.99	10.27	10.55	10.83	11.11	11.40	11.68	11.98	12.27	12.57	12.87	13.17	13.47	13.79	14.10	14.42	14.74	15.06	15.38	15.71
2	10.05	10.33	10.61	10.89	11.17	11.45	11.74	12.03	12.33	12.63	12.93	13.23	13.53	13.85	14.16	14.48	14.80	15.12	15.45	15.77
4	10.10	10.38	10.66	10.94	11.22	11.51	11.80	12.09	12.39	12.69	12.99	13.29	13.60	13.91	14.23	14.55	14.87	15.19	15.51	15.84
6	10.16	10.44	10.72	10.99	11.28	11.57	11.86	12.15	12.45	12.75	13.05	13.35	13.66	13.97	14.29	14.61	14.93	15.25	15.58	15.90
8	10.21	10.49	10.77	11.05	11.34	11 62	11.92	12.21	12.51	12.81	13.11	13.41	13.72	14.04	14.36	14.68	14.99	15.32	15.64	15.97
10	10.27	10.55	10.83	11.11	11.40	11.68	11.98	12.27	12.57	12.87	13.17	13.47	13.79	14.10	14.42	14.74	15.06	15.38	15.71	16.03

required. The e. m. f. developed is less than that of the iron-constantan couple but is large enough for accurate measurement.

Thermocouple Protection.—All thermocouples require protection against oxidation or the gases of combustion and are, therefore, placed in tubes that are sealed at the hot end. Platinum, platinum-rhodium couples are usually protected by tubes of porcelain or fused silica that may be covered by a second tube of carborundum, alundum, or metal, usually nickel. Platinum couples cannot be placed in metal protection tubes because of the danger of contamination. For base-metal couples, seamless steel tubing or the heavier grades of steel pipe, particularly double extra heavy, make satisfactory protection

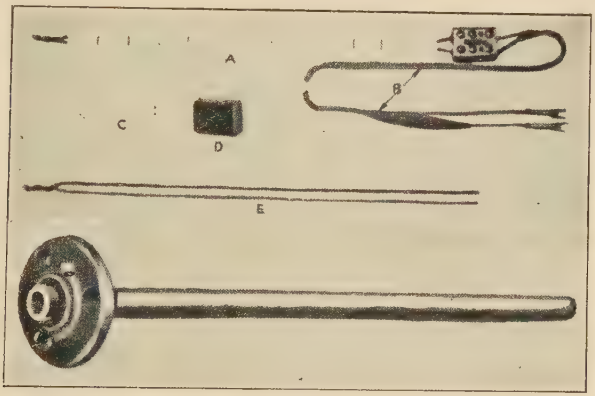


FIG. 120.—(*a*) Chromel-alumel couple and protecting tube.

tubes. Steel tube or pipe is sometimes used as the iron member of the iron-constantan couple, constantan wire being welded to the steel tube at the closed end. Still better protection is given by tubes of cast nichrome, which will give much longer service than steel. Several nickel-chromium alloys, some containing iron, are available for protection tubes. For special purposes, protection tubes are also made of such materials as carborundum, alundum, clay, graphite, and chrome iron. Iron-constantan couples are easily oxidized and are usually given further protection by packing in charcoal, graphite, mica, or other similar material. Platinum and chromel-alumel couples, on the other hand, should not be exposed to a reducing atmosphere, and air should, therefore, be admitted to the protecting tube. Examples of protection tubes are shown in Fig. 120.

Couple wires must be insulated as well as protected, and each wire is insulated by means of small tube of clay or porcelain such as those shown in Fig. 121. These insulators for base-metal

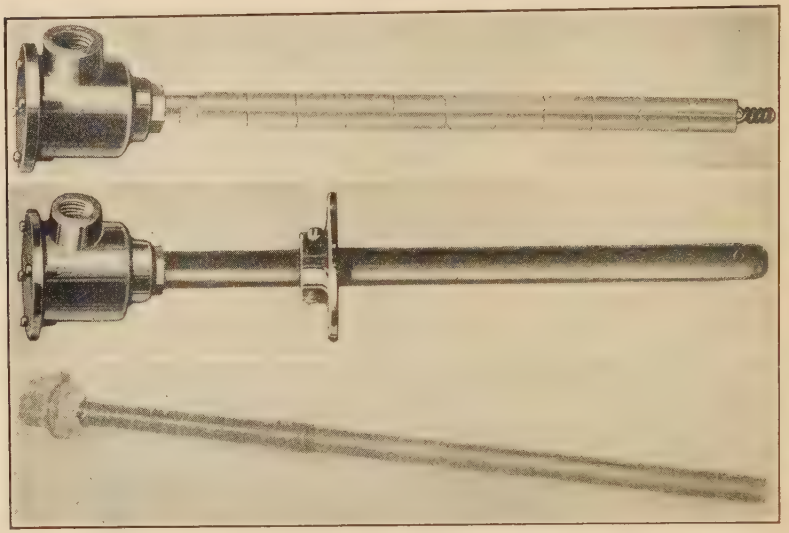


FIG. 120 (*Continued*).—(*b*) Protection tubes and insulators for thermocouples.

couples are usually about 1 in. long and may have either one or two holes. The single-hole insulator is preferred for chromel-

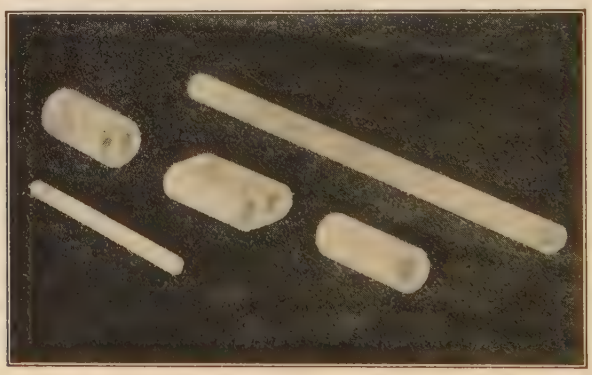


FIG. 121.—Insulators.

alumel couples because air can more easily reach the wire to form an oxide coating that is insulating as well as protective. Chromel-alumel couples can be used without insulators because

of the oxide coating formed when the couple is hot, but insulators are recommended for service, as the coating is easily broken. For checking, however, chrome-alumel couples can be inserted

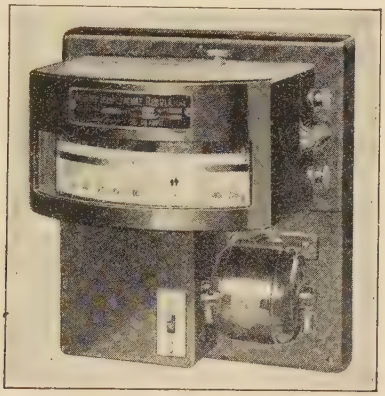


FIG. 122.—Millivoltmeter indicating controller. (*Hoskins Mfg. Co.*)

bare in the protection tube. After heating for a short time, an oxide coating is formed that is an electrical insulator. A bare couple of small wire is easily introduced into the tube with the operating couple.

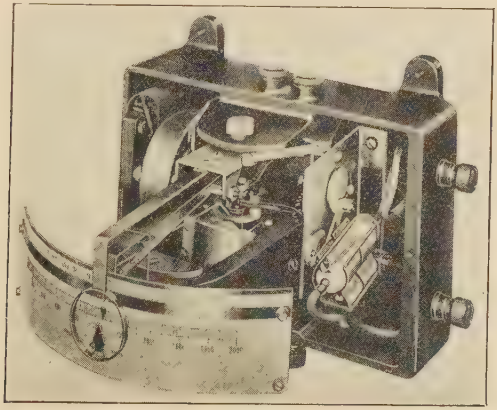


FIG. 123.—Interior of indicating pyrometer meter. (*Republic Flow Meters Co.*)

Measurement by Meter.—The e. m. f. developed by the couple can be measured by a millivoltmeter or by a potentiometer or by a combination of the two. The instrument may be calibrated for direct reading in millivolts or for temperature.

Calibrated in millivolts, the instrument may be used with any couple; in temperature it can be used with one type of couple only, that for which it is calibrated. Figure 122 illustrates a

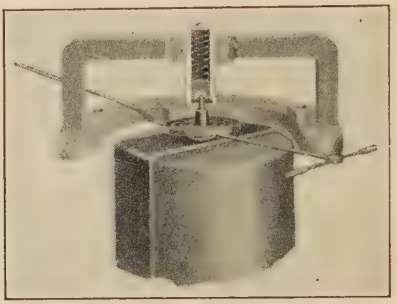


FIG. 124.—Galvanometer suspension. (*Hoskins Mfg. Co.*)

common type of millivoltmeter indicator. This instrument is equipped for the automatic control of fuel, as is also the indicator shown in Fig. 125. Figures 123, 124, 125, and 135 illustrate methods of galvanometer suspension.

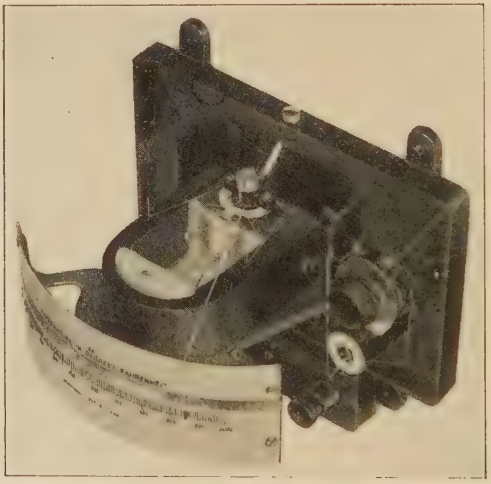


FIG. 125.—(*Courtesy Republic Flow Meters Co.*)

The millivoltmeter may have a low or a high internal resistance. The strength of the current due to the e. m. f. in the couple circuit depends upon the resistance of the circuit. A meter having a low internal resistance must, therefore, be

calibrated for the total resistance of the circuit. Dirty contacts, changes in the condition of the couple, and other conditions that alter resistance will change the reading of the instrument. By introducing a high resistance in the circuit, by means of a resistance coil in the instrument, and calibrating for this resistance, a varying resistance in the circuit will have little effect on the reading. Low-resistance meters have an internal resistance of about 50 ohms; high-resistance meters, up to 1,200 ohms.

Measurement by Potentiometer.—The resistance of the circuit can be neglected if the e. m. f. developed by the thermocouple is measured by a potentiometer, a voltage-measuring instrument The potentiometer develops a variable known e. m. f. that can be opposed to the unknown e. m. f. developed by the couple. The reading is made when the two e. m. fs. are equal and opposite. No current then flows in the circuit. Balance of the two currents is determined by a galvanometer

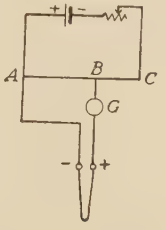


FIG. 126.—Potentiometer circuit.

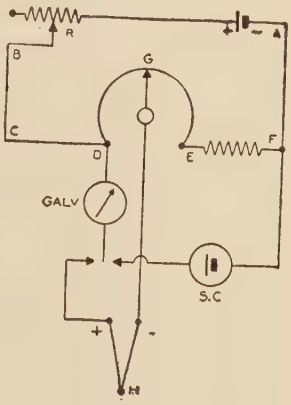


FIG. 127.—Potentiometer system including standard cells.

in the circuit and is indicated by a zero position of its pointer. The potentiometer for measuring temperature consists of a standard cell of known and constant e. m. f., a battery to provide a working current, a galvanometer, adjustable resistance to vary the e. m. f., and the necessary wiring. Figure 126 illustrates the principle of the potentiometer. A current from a battery flows through the circuit and through a slide-wire resistance *ABC*, setting up a difference in potential between *A* and *C*. One side of the thermocouple is connected to *A*, the other to the movable contact *B*. The drop in potential between *A* and *B* will be less as *B* moves toward *A* and more as *B* moves toward *C*. By moving *B* along the slide wire *ABC* until the galvanometer *G* indicates that no current is flowing, the e. m. f. of the couple

will be equal to the drop in potential between A and B, and if this is known, the e. m. f. developed by the couple will also be known.

The e. m. f. of a battery is not constant, so that some standard must be provided, and this is obtained by a Weston-type standard cell, a battery of known and constant voltage. In Fig. 127 is illustrated the wiring of a potentiometer pyrometer including a standard cell. The current of the battery circuit can be changed by means of the variable resistance R. By closing the contact between the standard cell and the galvanometer, the standard cell is connected to the potentiometer circuit at D and

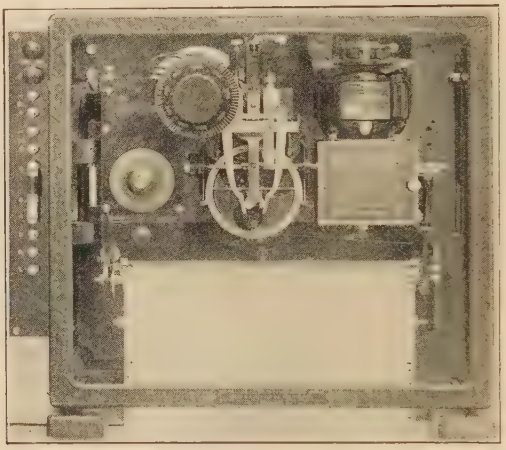


Fig. 128.—Potentiometer recorder. (*Courtesy Leeds & Northrup Co.*)

F and the galvanometer is in series with the standard cell. By adjusting the variable rheostat R, the fall in potential between D and F is made equal to the voltage of the standard cell, indicated by a zero position of the pointer of the galvanometer. The drop of potential in the slide wire of the potentiometer circuit DGE is now standardized and the instrument is ready for temperature measurement. The standard cell setting must be corrected from time to time. The slide wire DGE is provided with a scale calibrated in millivolts or in temperature direct. The potentiometer indicator does not indicate temperature directly but must be balanced manually.

The indicating potentiometer is a compact instrument. The battery may be included in the instrument, as in the portable

type, or separate dry cells may be provided to obtain longer life of the battery by the use of larger cells than can be conveniently placed in the instrument box. A wall-type indicator can be seen in the photograph, Fig. 138. The recording potentiometer, of which an example is shown in Fig. 128, is a rugged instrument and well designed mechanically. The delicate galvanometer needle has only a small part in recording. The operating mechanism is shown in Fig. 129 (*a*), and in detail in Fig. 129 (*b*). Shaft 6 is in constant motion, and cam 6*R* at the center of the

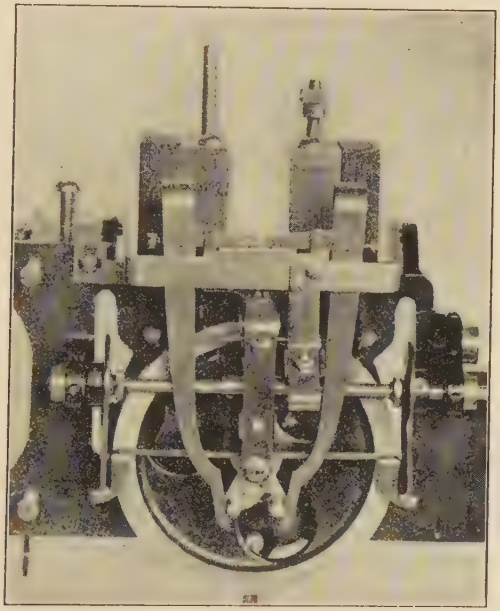
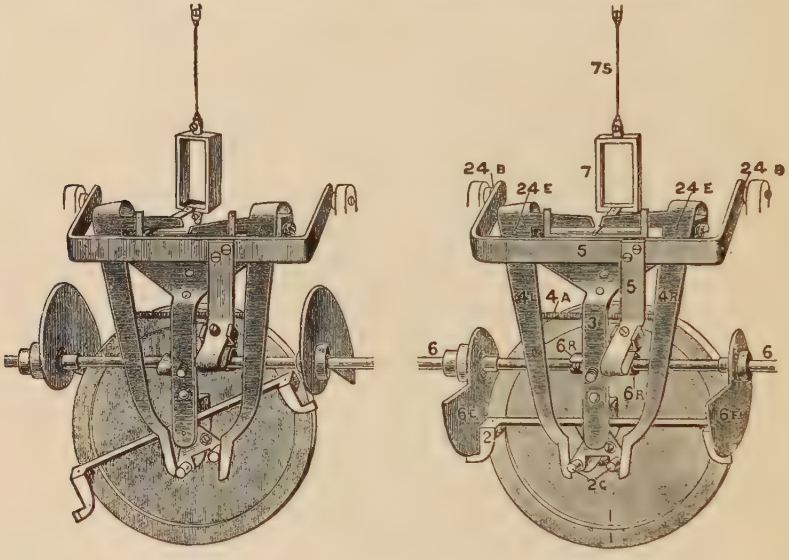


FIG. 129.—(*a*) Balancing mechanism for potentiometer recorder. (*Courtesy Leeds & Northrup Co.*)

shaft periodically lifts rocker arm 5. If the galvanometer needle is in zero position, its tip is lifted into the space between two lever arms 4*L* and 4*R*. But if the galvanometer needle is unbalanced, the needle will lie between the rocker arm and a lever arm, so that bar 2 will be shifted. Cam 6*R* separates bar 2 and disc 1 until the side cams 6*E* reach bar 2, which is then brought into tight contact with disc 1. The cams 6*E* then brings bar 2 into a horizontal position, this moving disc 1. This disc carries the slide wire of the potentiometer circuit, so that motion of the

disc changes the e. m. f. of the circuit. This movement of the disc continues until the galvanometer needle is at zero.

Deviation Meter for Potentiometer.—The recording potentiometer is also a direct-reading instrument, but the potentiometer indicator does not indicate directly as does the millivoltmeter but must be adjusted manually to balance the pointer in order to make a reading. This is a disadvantage when direct reading is desired. The potentiometer indicator, however, can be made to indicate directly within a range of tem-



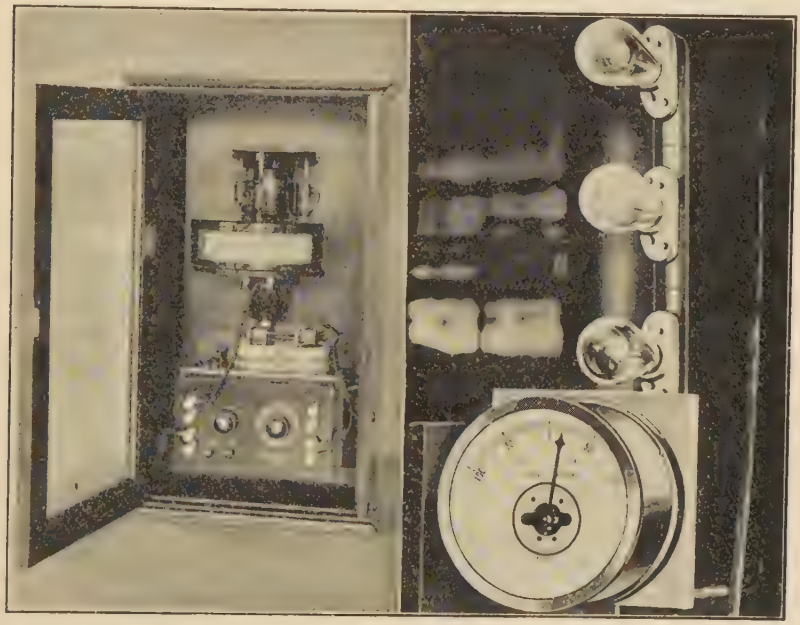
(*b*)

(1) Mechanism unbalanced. (2) Mechanism balanced.

FIG. 129 (*Continued*).—(*b*) Adjusting mechanism of potentiometer recorder. (*Courtesy The Leeds & Northrup Co.*)

perature of about 100° F. by the use of the so-called "deviation meter," an enlarged galvanometer placed outside of the instrument, as shown in Fig. 130 (*a*), a good illustration, although now obsolete. If the instrument is set for a given temperature, with the pointer at zero, any deviation from this temperature can be read directly from the deviation meter. The deviation meter can also be used in connection with the recorder, as shown in some of the photographs of furnaces, Chaps. XI and XII, with a deviation meter at the furnace some distance from the recorder. The instrument is shown in Fig. 130 (*b*).

Thermocouple Pyrometer System.—The thermocouple pyrometer system, consisting of the thermocouple, the meter or potentiometer, and the connecting wiring, is intended for the measurement of the temperature of a furnace or of a charge, but the actual measurement is merely of the difference in temperature between the hot and cold junctions unless provision is made to obtain measurement of actual temperature. The thermocouple must be properly placed, and the temperature of the cold



(*a*) (*b*)

FIG. 130.—(*a*) Potentiometer indicator with deviation meter early form, (*b*) deviation meter and signal lights at furnace.

junction must at least be constant and known. A pyrometer system that does not indicate temperature correctly may be worse than none at all. Some of the indirect methods described may be more satisfactory.

Position of Thermocouple in Furnace.—The thermocouple must be so placed that the temperature of the furnace will be known and, also, that the operator can tell when the charge has reached the desired temperature. Accuracy will depend more upon uniformity in the furnace than upon the pyrometer. In

stationary-furnace practice, both furnace and charge should be controlled by the pyrometer, and the thermocouple must be so placed that such control is possible. In a small furnace, the thermocouple can be inserted through the roof, but this position is not convenient if the furnace is large, and the couple will, therefore, be introduced through the wall. Large furnaces are better controlled if two couples are used, one at the front and one at the back. Furnace loads are not always of the same size, so that it is often convenient to be able to place the couple in different positions. In Fig. 91 (Chap. XI), two holes in the wall will be seen near the door, one close to the top, the other near the floor, so that the thermocouple can be placed above the charge at the proper height. Similar provisions can be made for another couple in the back wall.

In a stationary furnace, the thermocouple must be so placed that the temperature of the charge as well as the temperature of the furnace can be controlled. Both charge and furnace will be heated to the desired temperature, and the charge is then removed, as in hardening, or will be maintained at that temperature for some time, as in carburizing. The furnace will be cooled by the cold charge and then gradually heated to the required temperature in regular cycles. Continuous furnaces, on the other hand, are maintained at constant temperature. For processes that require long heating, for example carburizing, this temperature will be that to which the charge is to be heated. For rapid heating, however, in hardening for example, the temperature of the furnace will be well above the point to which the charge is to be heated, and passage through the furnace will be so regulated that the desired temperature will be reached as the charge leaves the furnace. Time and temperature must be standardized. In a long continuous furnace, the position of the zone of greatest heat may vary from time to time particularly with changes in the rate of travel, and the thermocouple must, therefore, be so placed that such variations will not affect the rate of heating. The best position is usually near the outlet end. Means for change of the position of the couple automatically can be provided.

Control of Cold-junction Temperature.—The thermocouple may be so placed that the temperature of the hot junction will be the same as that of the furnace or charge, but the reading of the meter may be incorrect unless some provision is made to control the temperature of the cold junction. The e. m. f.

developed by the thermocouple depends on the difference in temperature between the hot and cold junctions, and any variation in the temperature of the cold junction will result in a variation in the reading of the meter. Such variation is hard to avoid if the cold junction is close to the furnace. Platinum wire being expensive, the first platinum, platinum-rhodium couples were comparatively short, the cold junction, therefore, being near the furnace. To obtain a uniform temperature, the cold junction was sometimes placed in a water jacket and cooled by flowing water, a method now practically obsolete. Thermocouple extension and compensating lead wire make it possible to remove the cold junction from the furnace to the meter or to some position where the temperature will be constant.

Thermocouple Extension Leads.—Thermocouple extension leads are flexible wires of the same materials as the couple. Each couple wire is connected to a lead wire of the same composition, and the extension may continue to the meter. Care should be taken to connect like wires. This is the simplest method of removing the cold junction from the furnace, but the meter must be so housed that its temperature does not vary or must be provided with a compensating device to correct for changes of temperature that may occur by methods that will be described. Thermocouple extension leads are used most commonly with iron-constantan couples because of the comparatively low price of the wire and are also used, to some extent, with chromel—alumel, although compensating leads are less expensive and, therefore, generally preferred.

Compensating Leads.—Platinum, platinum-rhodium and chromel-alumel couples can be provided with compensating lead wire for cold-junction correction, such lead wire being of less expensive materials than those of the couple. Such compensating leads are a secondary couple having the hot junction connected to the cold junction of the couple and so imposing an added e. m. f. to the circuit with rise in the temperature of the cold junction of the couple. Within the ordinary range of cold-junction temperature, the e. m. f. developed by the compensating leads is practically the same as the e. m. f. developed by the couple.

Platinum, platinum-rhodium couples are compensated by lead wires of copper and an alloy of copper and nickel, known as "Bristol compensating leads." Chromel-alumel couples can be

compensated by copper-constantan. These leads do not compensate individually. Bristol leads compensate to within 10° F. (5° C.) in a range up to 200° F. (95° C.). The close correspondance between chromel-alumel and copper-constantan is shown in the tables of e. m. f. and temperature. Closer compensation is obtained by a slight variation in the composition of the constantan.

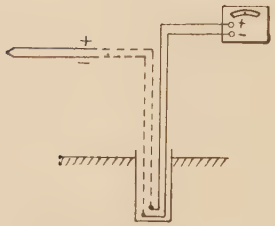


Fig. 131.—Buried cold junction.

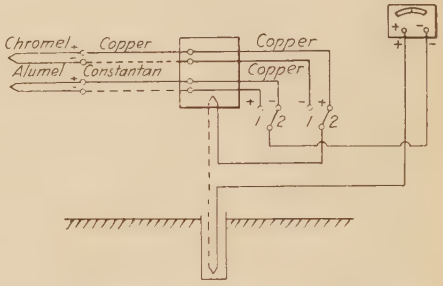


Fig. 132.—Wiring diagram buried cold junction with common zone box.

Position of Cold Junction.—Thermocouple extension or compensating leads may be extended to the measuring instrument, but to reduce the expense, the cold junction may be placed near the furnace and buried in the ground to obtain a constant

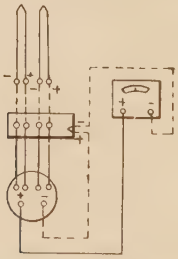


Fig. 133.—Wiring diagram commmon zone box.

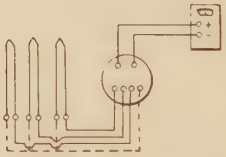


Fig. 134.—Wiring diagram compensating lead in common.

temperature. From the buried cold junction, copper leads extend to the measuring instrument. In practice, a pipe 3 to 5 in. in diameter is driven in the ground to a depth of 5 or 6 ft., thus providing a well in which the cold junction can be placed. The principle is illustrated in Fig. 131. Buried cold junctions are no longer common because replaced by automatic compensation.

Other methods of wiring, once quite common but now largely replaced by extension and compensating leads to the meter provided with automatic control of the cold-junction temperature, are shown in Figs. 132 and 133. The cost of lead wire can be reduced by the method of Fig. 132 or by the use of a common lead wire for all couples, as illustrated in Fig. 134. This method, however, it not recommended because of troubles that result from dirty contacts and shorts, particularly grounds.

Compensation at Meter.—Although more expensive than the methods just described, general practice now connects the couple to the meter by flexible thermocouple leads or by compensating leads. The meter is so housed that no wide variation in its temperature can occur, or else it is provided with hand- or auto-

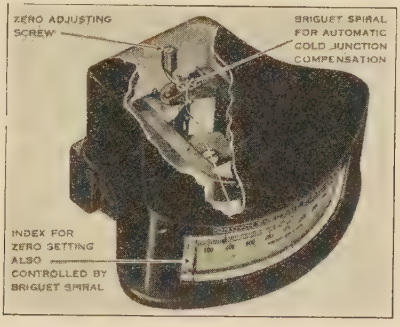

ZERO ADJUSTING SCREW
BRIGUET SPIRAL FOR AUTOMATIC COLD JUNCTION COMPENSATION
INDEX FOR ZERO SETTING ALSO CONTROLLED BY BRIGUET SPIRAL

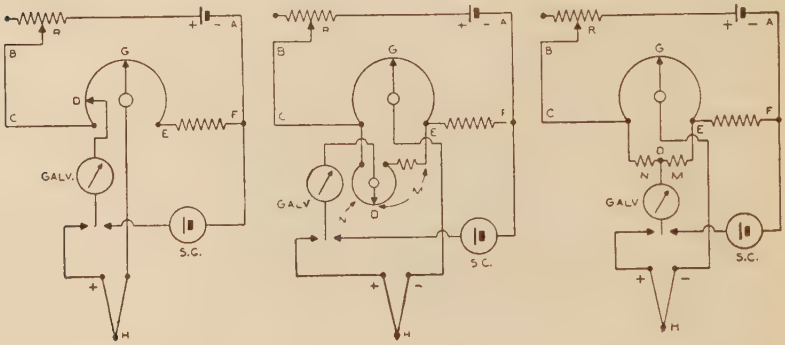
FIG. 135.
(*Courtesy Brown Instrument Co.*)

matically operated devices for compensating any variation in the temperature of the cold junction, which is brought to the meter by the leads. Indicating meters and recorders may be corrected by varying the zero setting to correspond with the temperature of the cold junction, but such instruments are now usually equipped with a bimetallic spring that automatically corrects the position of the needle, as shown in Fig. 135.

A cold-junction correction of a potentiometer can be made manually by providing a separate contact that can move over a portion of the slide wire, as illustrated in Fig. 136 (*a*). In practice, a second slide wire is placed in parallel with the main slide wire, as in Fig. 136 (*b*), and the cold-junction correction is made by moving contact D as required. Automatic compensation is obtained by means of a nickel coil, as illustrated in Fig. 136 (*c*). On one side of D, a fixed point, is placed a constant-resistance coil M

having a zero coefficient of resistance, and on the other side a nickel coil N having a high-temperature coefficient and placed near the cold junction. M and N are so proportioned that an increase of temperature of the cold junction has the same effect as moving contact D on the slide wire. The nickel coil can be removed from the instrument to the cold junction wherever that may be placed.

Arrangement of Instruments.—In early pyrometer installations, one indicator was used with several couples and connected by means of a switch. If a record was desired, multiple-point recorders were added. The single indicator still remains, but the multiple-point recorder has been replaced almost entirely



(*a*) (*b*) (*c*)

FIG. 136.—Principle of manual control of cold junction in potentiometer. (*a*) Adjustment on slide wire, (*b*) adjustment on extension of slide wire, (*c*) principle of automatic control of cold junction in potentiometer.

by the single-point or two-point recorder for greater accuracy and because of the development of automatic control. The single indicator will be replaced by individual controlling indicators for each point if furnace control is to be automatic and no record is required.

Lead wires may connect directly with the meter, but, particularly in large installations, connecting panels are to be preferred. These are arranged to permit connecting any couple to any instrument. Figure 137 illustrates connecting panels for a large installation. Figure 138 shows a pyrometer room in which the recorders are concentrated, the equipment including a wall-type indicator. In smaller installations, the instruments may be placed near the furnaces, thus doing away with the pyrom-

eter room. In all modern installations, both indicator and recorder are placed for the convenience of the operator, and the

FIG. 137.—Connecting panel boxes and conduit arrangement for pyrometer system.

FIG. 138.

recorder is no longer considered a secret device for checking the operator and placed in offices at some distance from the furnace room.

Connecting Thermocouples.—Because of the feeble current supplied by a thermocouple, connections must be tight, particularly with a millivoltmeter. Thermocouples on the market are, therefore, frequently provided with special heads that fit standard protecting tubes, heads equipped with special connectors of which examples have been shown (Fig. 120). For the small plant not equipped for the manufacture of couples, equipment of this kind is usually required, especially if iron-constantan couples that require packing are used. Fittings, however, can be made at small expense for chromel-alumel couples. Pipe flanges fastened to the open end will hold a tube in place. Connection from couple to lead wire can be made with ordinary brass connectors, which can be insulated by asbestos tape and water glass. One layer of this tape, wet with water glass, is placed between the setscrews of the connector, and two connectors fastened together by another strip of asbestos tape prepared in the same way. Other simple and satisfactory methods of connecting are available.

Checking Thermocouples for Service and in Service.—Thermocouple wire will vary in composition and condition and will also deteriorate in service, so that thermocouples must be checked before entering service and also in service. The checking of couples for service is based upon test at certain fixed points —the boiling points of certain compounds or the melting points of pure metals of which examples are given in the following table:

	Degrees Fahrenheit	Degrees Centigrade
Water boils	212	100
Naphthalene melts	424.5	218
Freezing or melting points of metals:		
Tin	450	232
Lead	621	327
Zinc	787	420
Aluminum	1220	660
Copper	1981	1083

The accuracy of a thermocouple may be determined by checking the melting points of pure metals, but this is for the laboratory rather than the shop. Standard couples can be checked by such methods, but industrial couples will be checked against

standard couples. For such checking, a small tube furnace, of the type used for determining carbon by combustion, or a small muffle furnace can be used. A molten bath has an advantage in that the temperature of the bath is uniform throughout and is easily maintained, permitting checking a number of couples at one time, which, however, must be provided with protection tubes. Couple wire is not always homogeneous throughout and must, therefore, be tested at different depths of immersion and, more particularly, at the depth of immersion in service. Because a couple is formed by contact between two dissimilar metals, secondary or parasite currents will be developed if the metal is not homogeneous. Parasite currents can be developed by bending the wire, particularly platinum.

The large manufacturer can provide a department for the manufacture of thermocouples, but the average user must purchase them. Couples should always be bought from a reliable source of supply that carries a large stock and has proper facilities for checking and standardizing wire.

The average user will have little difficulty in checking thermocouples in a small furnace such as mentioned. The two couples, checking and service, are placed close together in the furnace, properly insulated, and connected to the same instrument by a two-way switch. This instrument may be calibrated in degrees if the couples are of the same materials but, if not, should be calibrated in millivolts. If the furnace is too short for testing at different depths of immersion, a test for parasite current can be made by passing the flame of a burner along the wires and watching for any movement of the pointer of the instrument. After checking, couples should be supplied with a tag showing the error and are then ready for service.

For checking couples in service, another pyrometer is usually provided so that the entire system can be checked—advisable if meters are employed, although not so necessary if the measurement is made by a potentiometer. Checking and service couples should be placed close together, which is sometimes a problem to accomplish. A second hole through the wall will permit placing the two couples in the furnace near together, or room may be left in the tube for the insertion of a checking couple. If the furnace temperature is constant, the service couple may be removed, and the checking couple placed in the tube, but this method is not entirely satisfactory and impossible if the couple

is packed. For inserting in the tube with the service couple, a chromel-alumel couple of small gage is useful, because no insulators are necessary. Service couples should always be checked in place and not removed from the tube even if this be more convenient. A couple may be correct in place and yet vary if checked outside.

Double-couple System.—The regular checking of individual thermocouples in a large plant is an expensive process and does not insure against sudden changes between the periods of checking. A constant check with little labor required can be obtained by employing two thermocouples at each point, two couples in a protecting tube, connecting one to an indicator and the other to a recorder. That the two couples will fail at the same time is improbable, but for further protection against this chance the two couples should be put into service at different times. The double system has proved its value in a number of plants and has more than saved the extra cost of wiring by doing away with checking.

Control of Furnace Temperature.—Control of furnace temperature was once entirely dependent upon the operator who determined temperatures by an indicating instrument and acted in accordance with the readings. If recorders were supplied, the operator might not see them, as they were often kept in the office and sometimes even in the home of the superintendent, and multiple-point recorders were preferred for economy even if kept in the furnace room. Now the recorder is usually the operating instrument covering but one or two points and may also regulate the furnace by means of control devices. If recorders seem unnecessary, the burden of automatic control may be thrown on an indicating instrument. Manual control has by no means gone, for it is frequently more satisfactory and less expensive than automatic control, but even with manual control of furnaces the pyrometer may take over part of the work.

Central-control Signal System.—Regulation of a large number of furnaces is no simple task if the operator is obliged to go from furnace to pyrometer and back. The first step toward assisting him came with the introduction of central control and a signal system. All the thermocouples are wired to one indicator that is under the observation of one operator who checks temperatures continually and signals to the furnace operator. Each furnace is provided with a set of lights of different colors, usually three to

indicate whether the furnace is below, at, or above the temperature desired, and these lights are operated by the central observer. A record may be made of each reading, or recorders may be provided. This central control system took a large burden from the furnace operator but was "pretty poor use to make of a man" and has been replaced by automatic-light control or by burner control.

Automatic-light Control.—As in the system for manually operating a signalling system, automatic lighting control requires three lights with separate lighting systems for low, high, and at

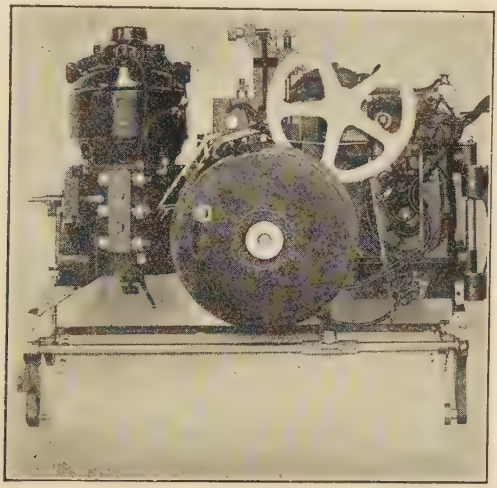


FIG. 139.—Control dials potentiometer recorder. (*Courtesy Leeds and Northrup Co.*)

temperature. For a furnace equipped with two couples and controlled by a two-point recorder, a fourth light can be added that shows for which of the two points the signal is given, as illustrated in Fig. 58 (Chap. XI). The pyrometer instrument is provided with some device for making the proper contact but otherwise has no part in the operation of the controls. The method of making contact with a potentiometer recorder is shown in Fig. 139. Behind the disc carrying the slide wire and on the same shaft are two discs, each having a hump on the edge. One disc is arranged to make the contact for the low side; the other, for the high side through a flat spring. Contact for the light that indicates the correct temperature is made when

the bearing point of the spring drops into the hollow between the two humps, and any range of temperature desired may be

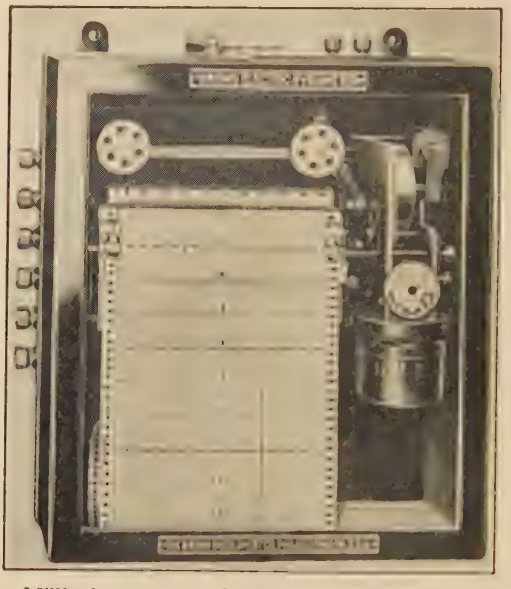


FIG. 140.—Millivoltmeter recorder. (*Courtesy Brown Instrument Co.*)

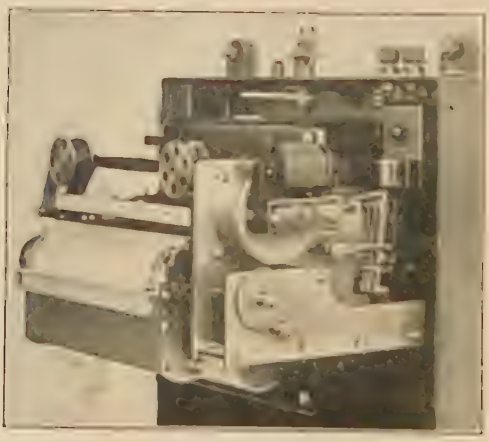


FIG. 141.—Millivoltmeter recorder. (*Courtesy Brown Instrument Co.*)

obtained by proper spacing. The disc carrying the slide wire is moved to the position that corresponds to the temperature desired, and the two contact discs are then fastened on the shaft

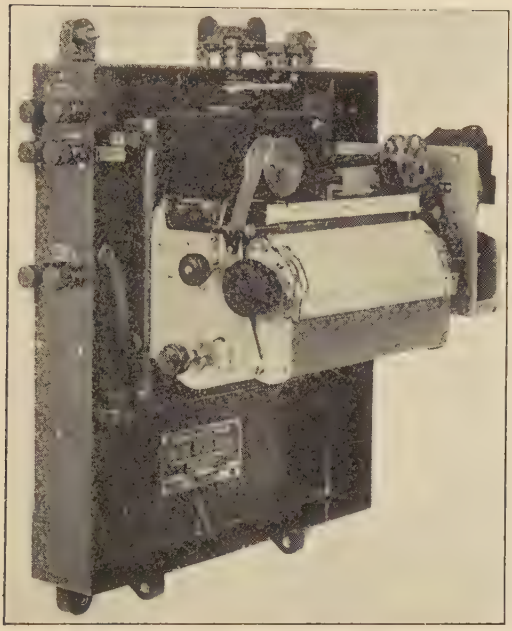


FIG. 142.—Millivoltmeter recorder. (*Courtesy Brown Instrument Co.*)

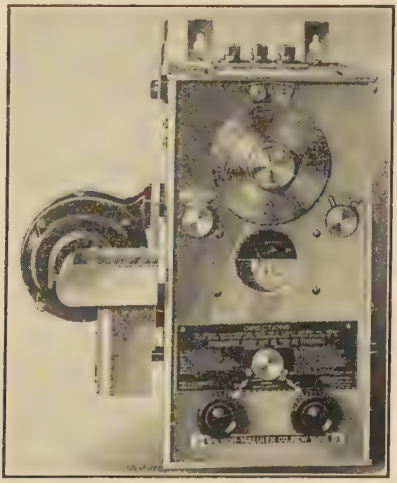


FIG. 143.—(*a*) Indication controller. (*Courtesy Wilson-Maeulen Co.*)

in the proper position. An indicating controller operates in much the same way but without making a record.

Figure 140 shows a six-point recording millivoltmeter, the operating mechanism being illustrated in Figs. 141 and 142. Figure 143 (*a*) shows one type of indicating controller. A series of these instruments can be operated by one motor, as illustrated in Fig. 143 (*b*).

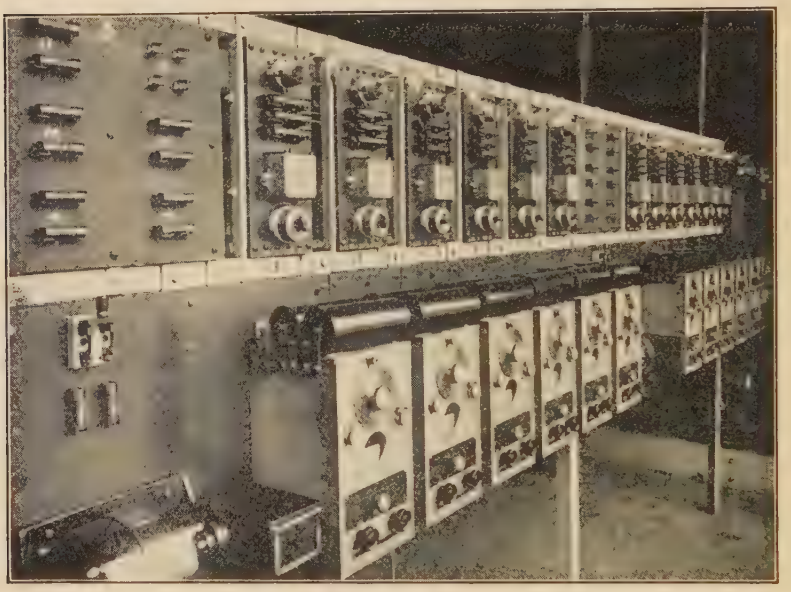


FIG. 143 (*Continued*).—(*b*) Series of indicating controllers. (*Courtesy Wilson-Maeulen Co.*)

Automatic Burner Control.—Such devices will operate automatic burner controllers as well as lighting circuits, devices that will turn on or off the fuel supply when the temperature of the furnace falls below or rises above the point desired or that will regulate the supply. The simplest device for on and off control is the solenoid, an electromagnet illustrated in Fig. 144. The fixed and movable armatures of the solenoid, cylinders of soft steel, are placed in a central tube of brass around which is wound a coil of fine insulated wire. Passage of current through the coil magnetizes the armatures, which then come together. To the movable armature is attached a lifting device for opening the valve when the passage of current brings the two armatures together. When the current is cut off, the movable armature

drops, closing the valve. Successful operation depends upon having the correct distance between the two armatures, about $\frac{1}{8}$ in.

The solenoid of Fig. 144 is shown in service in Fig. 145. To the movable armature is attached a U-bolt by which a whistle valve, connected in the oil line, is opened. Butterfly valves for air can be operated by attaching a lever arm to the movable armature. The solenoid itself is comparatively simple in

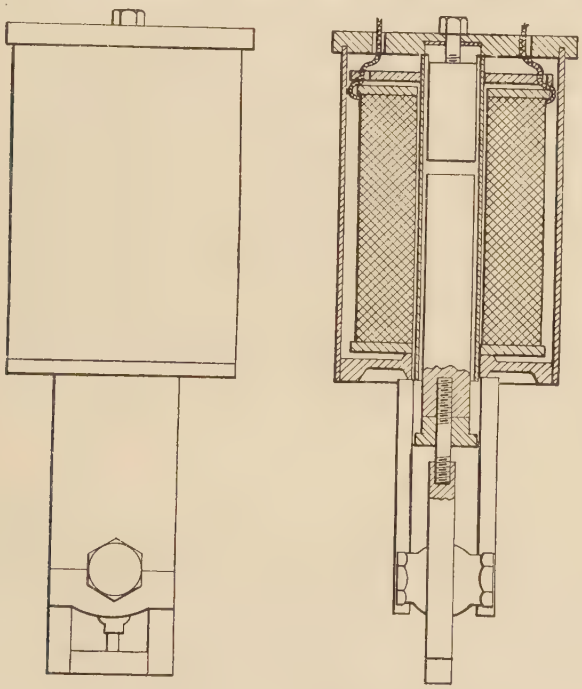


FIG. 144.—Solenoid.

construction, but ingenuity is necessary in adding devices for operating valves.

The motor-operated valve for on and off control is sometimes preferred to the solenoid, because less attention is required in setting valves or because the motor-operated valve can operate more than one burner. A motor-operated control valve is shown in Fig. 146.

Automatic control is no panacea for heat-treatment ills. The primary purpose is the saving of labor, particularly skilled labor. A trained burner operator can hold the temperature of a furnace or of a number of furnaces as closely as the automatic

FIG. 145.—Solenoid valves.

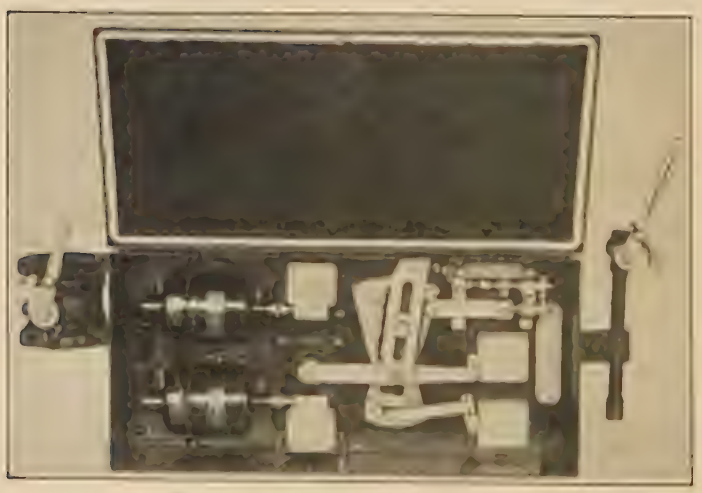


FIG. 146.—Motor-operated valves.

device if provided with automatic lights or other means by which he can watch temperature without constant reference to a pyrometer. If such skilled labor is required for purposes other than burner control, automatic control may be only an additional expense. On the other hand, automatic control finds a definite place in the operation of continuous furnaces fed automatically and for heating operations that require time but not much attention.

Optical Pyrometers.—Optical pyrometers are seldom used in heat treating steel, because they will not measure temperature below the visible colors and because of the greater ease of control possible with the thermocouple pyrometer. The field of the optical pyrometer may be said to begin where the field of the thermocouple or resistance pyrometer ends, although the two fields overlap. The optical pyrometer is serviceable for measuring temperatures well above those of heat treating or for special operations, for example in measuring the temperature of rod being rolled. Optical pyrometers are of several types. One type has a standard source of light—the amyl-acetate lamp—and measurements are made by a comparison between brightness of the field illuminated by the standard source of light and brightness of field illuminated by the source of heat to be measured, the two fields being matched by means of an adjustable wedge of black glass. An electric light, standardized against the amyl-acetate lamp, serves as the standard light in another type of optical pyrometer. By changing the resistance of the lamp circuit, the light intensity emitted by the filament of the lamp is blended with the intensity of the light emitted by the source of light to be measured, and the current required is measured. The simplest form of optical pyrometer is known as the "disappearing-filament" type. In its simplest form, this type is merely a small electric lamp containing a filament slightly heavier than that ordinarily employed for such lamps. The filament is in view when the pyrometer is sighted upon the source of heat. A current of electricity flowing through the lamp is adjusted by a rheostat until the light intensity of the filament is the same as that of the object sighted upon, a point reached when the filament is almost invisible. The instrument is calibrated by sighting upon objects at known temperature.

Radiation Pyrometers.—Radiation pyrometers contain a small thermocouple upon which the rays from the source to be

measured for temperature are focused. The e. m. f. developed is measured with a meter calibrated for temperature. Several types of radiation pyrometers have been developed some of which have a fixed focus so that the measurements can be made without regard for distance, while others require focusing for each determination.

CHAPTER XIV

THE STEEL-TREATING DEPARTMENT IN THE SCHEME OF PRODUCTION

Planning and Housing the Heat-treating Department.—In the early stages of the development of modern heat treating and before the necessity for closer control had been shown, the heat-treatment department was placed in the factory without much regard to its connection with other processes. In many industries, heat treatment was looked upon either as a dark secret or as a necessary evil to be hidden away in any convenient corner as dark as possible, darkness being assumed as necessary for determining hardening temperatures by color. Such conditions are now very rare, and heat-treating departments have taken their proper place in the scheme of production and are properly housed. This has accompanied the development of modern factory methods and, also, the development of instruments for accurate control of processes.

One of the important requirements of modern production is a close connection between the various operations, not only to avoid as much handling and transfer as possible, but also to reduce the inventory of parts in process. Such a close connection is not difficult in the operations of the machine shop, but the operations of heat treating are so radically different from these that no close connection would seem possible. Because steel treating requires furnaces operating at high temperatures, which give off large quantities of hot waste gases, the handling of hot metal, and the use of equipment very different from that of the machine shop, it is not surprising that the processes are usually segregated in buildings designed to meet the operating conditions.

Although a very distinct separation might seem to be required, it has been quite common practice to make some sort of connection by bringing the heat-treatment department into buildings designed for other purposes. When such buildings contain more than one story, very uncomfortable working conditions may result

not only in the heat-treatment department but also in other departments placed nearby. It is possible to supply cooling and ventilating equipment, but even with this it is not always possible to obtain good working conditions, and, furthermore, the expense of installing and maintaining such equipment may more than balance any gain due to location. If the department is so placed without some advantage of location in connection with other processes, operation may be costly.

The Separate Department vs. Locating Equipment in the Production Line of Other Departments.—Heat treatment after forging can be made part of a continuous process without much difficulty, because the operating conditions are much the same, and, therefore, the addition of heat-treating furnaces offers no particular problem from that standpoint. Introducing heat-treating equipment into a crowded forge shop may be a problem but no more so than rearranging the equipment in a crowded machine shop. In either case, space is necessary. Machining may follow forging in a continuous line, but the machines must usually be at some distance from the hammers. For this reason, a separate machine shop is, perhaps, better practice. The shop, however, can be so placed that production is continuous. This method of handling forgings will not apply if forgings are made in one plant and heat treated and machined in another entirely separate, and the combination of heat treatment and machining equipment for continuous operation will not necessarily be economical because of the handling necessary at one place or the other.

Forging and heat treating can be carried on together, because the operating conditions are much alike, but heat treating and machining are far apart and require, generally, quite different methods of housing. The heat-treatment process, however, can be divided into two classes—one including processes that can, with suitable equipment, be carried on in the ordinary machine shop, processes such as hardening and drawing; the other, processes that are not easily included in the machine line of which carburizing is an example, a process that requires a long time, the handling of hot metal and containers and of dusty compounds. The electric furnace, giving off little heat and no waste gas, particularly if continuous, has made it possible to carry on the simpler processes in the production line, and the rotary-retort furnace may often permit carburizing. But, in

general, processes requiring time and special handling are carried on in a separate department.

As a modification of this method of locating the processes in direct connection with the production line, a separate room, or even building, is sometimes used in which the necessary furnace equipment is placed near to but distinctly separate from the department or departments to be served. The individual building is more frequently used in large plants, one unit being attached, perhaps, to the forge shop, another to the stamping plant, other units being spread around in a similar way. The application of this method will depend upon the work to be handled, the size of the plant, and the space available.

The close connection of a series of production operations lowers the cost directly by reducing handling and transfer expense as well as material in process and stock. The expense however, may be increased in other directions. Special furnaces, having high installation and maintenance cost, and other equipment, may be required to avoid uncomfortable working conditions; the cost of supplying fuel and of supervision will usually be higher when the heat-treating processes are scattered than when they are carried on in a unit plant; shop floor space may be too valuable for heat-treatment purposes. Before processes are taken from the unit plant and divided up among other departments, the respective costs of installation, upkeep, operation, and overhead charges should be compared, not only for the entire group, but also for each process.

Under average conditions, when the simpler operations, as, for example, heating, quenching, and drawing or light annealing are to be applied to work of no great size, the advantage of cost or of operation may be in favor of a direct connection with the production lineup. On the other hand, the handling of large quantities of heavy work may require a separate unit. If a number of such processes must be carried on for which a distinctly separate building is provided, it may prove less expensive to locate all heat-treatment processes in one unit. Including heat-treating operations in the production line will often pay in spite of an increase in the direct cost of equipment and operation if the shop is manufacturing a large quantity of one part or parts much alike and requiring the same treatment. But if the output consists of comparatively small numbers of parts that are quite different, requiring different treatments, con-

tinuous line production will rarely pay. The arranging of equipment for economical production cannot be based on "style" or theory but must result from a thorough and exhaustive analysis of cost. Conditions vary too much to permit setting definite rules, but the important points have been mentioned.

Although large increases in production, which either limit the space available or increase transfer distances, have been responsible for introducing many heat-treatment operations into shops intended for other purposes, the unit plant still remains average practice. This combining of heat-treatment processes in one production unit does not necessarily imply a wide separation from other departments. In modern compact factories, the unit heat-treatment department may be located very conveniently to all or to most of the other departments from which or to which work is process flows, with little handling and transfer required. In larger factories occupying considerable ground, more than one heat-treatment building may be provided, each, however, being a unit in which all the necessary processes are carried on, separated from other production operations.

The Unit Plant—Location.—The unit heat-treatment plant being more commonly used in general practice, methods of locating it in the scheme of production will be discussed. In practice, certain methods of location have been developed of which a number can be used directly or can be modified easily to meet nearly all production conditions, whether the plant be large or small, scattered or compact. In all department location, certain principles are involved that take into account not only the details of handling and transfer but also those of receiving and shipping, of manufacture, and of the requirements for future expansion.

In Fig. 147 is illustrated a simple example of modern methods of layout in which all the factors mentioned have been well coordinated. Production in this plant is all in a straight line with no "back tracking", and expansion has also been arranged for in a similar way, all units growing in the same proportion and in the same relation. Although this layout is designed for a forge shop and heat-treatment plant, the method is quite suitable for other lines of production.

In Fig. 148 is shown a similar layout applied to machine-shop production combined with heat treatment. Here the production flow is less direct on account of the finishing operations following

heat treatment. This layout can be simplified by locating storage space for raw material along the side of the building or on the platform.

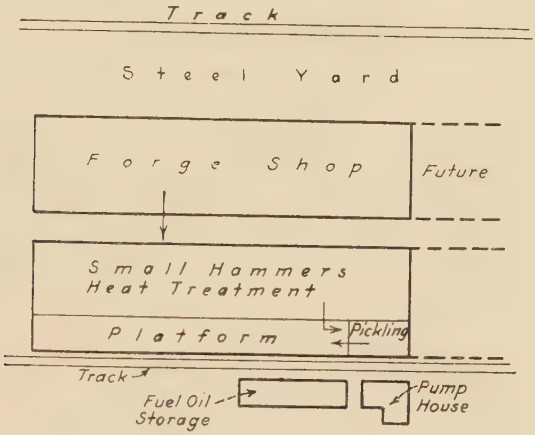


FIG. 147.

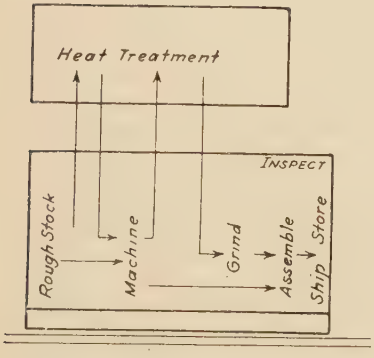


FIG. 148.

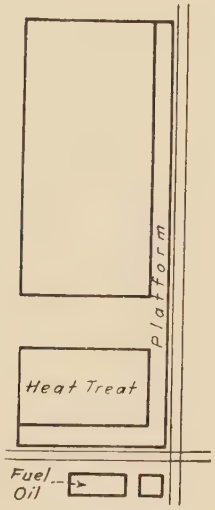


FIG. 149.

Figure 149 illustrates a further modification of this method of layout adapted to a long and narrow ground space, the heat-treatment department being placed at the end instead of at the side of the building. Transfer distances will be somewhat

greater, but if the finishing operations of the shop are located at the end of the main building next to the heat-treatment plant, this is not so important.

This type of layout, with the various modifications possible, is well adapted to a production of one type, for example the manufacture of forgings, or for a standard production that does not vary widely. When, however, production from a number of shops must flow to and from the heat-treatment plant, usually involving the handling of very different classes of work, such an arrangement is not always possible. If the various shops are some distance apart, much handling and transfer may be necessary. Modern factories, however, are usually compact even

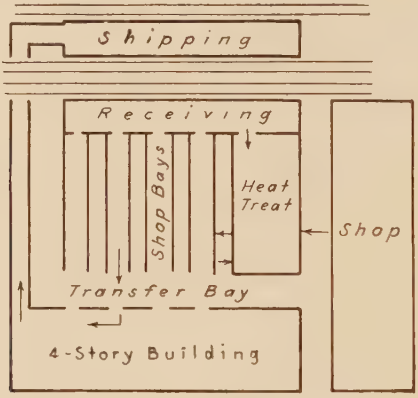


Fig. 150.

with a large and varied production, and in such plants the heat-treatment department can usually be located in close connection with the other shops with which it deals. The method of location may be very similar to that illustrated in Figs. 147, 148, and 149, many of the same principles being involved.

Figures 150 and 151 represent a modern arrangement of shops and assembly units in which the heat-treatment plant has been centrally located to take care of a complicated production. Here the shops delivering to or drawing from the heat-treatment department are located in close proximity. Transfer distances are short and the requirements of receiving and shipping have been met. In such compact plants, processes such as forging or casting are not easily included, but such products will be

made outside and delivered to the shops by rail. When ground is not limited, however, such processes may also be included in the scheme, as shown in Fig. 152.

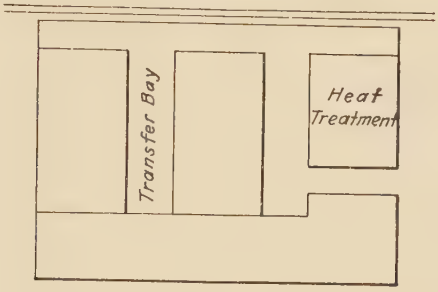


Fig. 151.

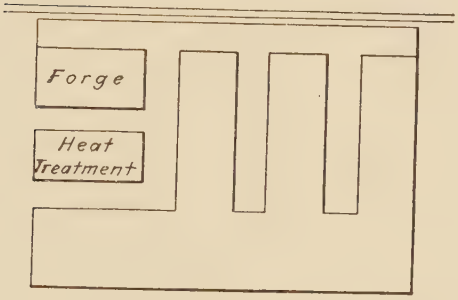


Fig. 152.

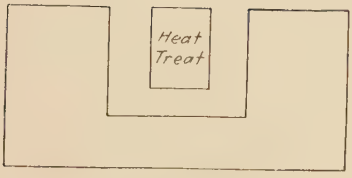


Fig. 153.

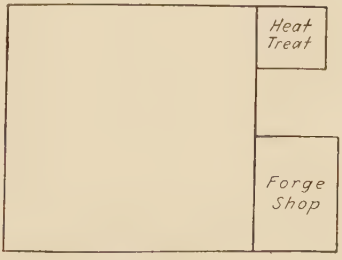


Fig. 154.

Figures 153 and 154 represent common methods of locating a separate heat-treatment plant in connection with shops that are small or in connection with older types of construction. Both arrangements are quite convenient for single- or two-storied buildings, and if spur tracks are laid to take care of receiving and shipping, handling and transfer can be simplified.

All of these layouts are in use and have been selected as typical examples of current practice. In each of them, the aim has been to coordinate all of the shops and to include the heat-treatment department as part of the scheme but as a detached unit so that it can be housed in a properly constructed building. In each case, it is not only located centrally and close to other departments from which it receives or to which it sends work in process, but also is so located that raw materials to be heat treated before other operations can be received directly from the car. Such compact units represent the modern tendency in factory design. The principles brought out in these layouts can be applied regardless of the size of the plant or of variation in its production.

Although these principles are most easily applied to new construction, it is possible to work out similar types of layout in many plants of older design. Buildings used for one purpose can often be adapted to other purposes, and by such rearrangement departments working on the same parts can be brought close together. If buildings of one-story construction are available, it may be possible to house the heat-treatment department in the same building with others connected in production.

Such treatment may not be difficult when a number of buildings are available, but if all departments have been housed in one or in a group of buildings of several stories, of which examples are common, it is sometimes no simple matter to make a readjustment. In such buildings it has been common practice to locate the heat-treatment department on the ground floor without much regard to ventilation, resulting in exceedingly difficult working conditions with a high labor turnover. In many factories of this type, it has become necessary to change such conditions, and in some of them the problem has been solved by placing the heat-treatment department on the top floor. Such location might appear to add to the expense of handling and transfer, but in many of the factories that have buildings of the conventional type with several stories, much of the production starts at the top floor and moves down to the ground. Placing the heat-treatment department on the top floor may not, therefore, increase the amount of handling to any great extent.

Although this method of location may be a comparatively easy solution of the problem in a few factories, top-floor space

may be of more value for purposes other than steel treating if production is complicated. To haul a large amount of heavy pieces to the top floor is costly, and, furthermore, the floor must be strong to hold heavy furnaces. For reasons of this kind and for others that have been given, the separate building is usually preferred for steel treating unless furnaces can be placed in the line of production machines.

Building Design.—When the heat-treating department is given a separate building, one-story construction should be the first thought, and the building should be placed as close as possible to the other shops with which it operates, but with some allowance for space between. If too close, fire hazards may be increased, ventilation be difficult, not only in the heat-treatment department but also in the adjoining shops, and handling and transfer troublesome on account of the lack of passageway. It is a good rule to require that the heat-treatment building be at a distance from other buildings, on three sides if possible.

Items of Cost That Influence Location.—Whether a new plant is to be built or an old one is to be rearranged, the proper method of arrangement will, in final analysis, depend upon cost. Perhaps, in some factories, the conditions under which the operators must work will require an equal amount of attention, but even this can be calculated in dollars and cents. High labor turnover can be responsible for high cost. Other items that can be calculated more exactly have already been mentioned. Summarized, they are:

Value of floor or ground space.
Cost of handling and transfer.
Cost of delivering supplies.
Cost of installing and maintaining.
Cost of superintendence.

These are the principal items to be considered in selecting a location for the steel-treating department and apply to practically all plants regardless of size. The cost for each possible arrangement can be estimated, and information thus obtained that will at least serve as a guide.

Summary of Methods of Locating the Heat-treating Department.—Several methods of locating a steel-treating department have been discussed, covering the principal methods of practice. Steel-treating equipment can be placed:

As a unit with other departments in the factory.

In a number of separate departments, dividing the operations and placing the equipment in the production line or in rooms in close proximity.

In a number of separate buildings each attached to that part of the main factory from which or to which its production passes.

In a distinctly separate building as a complete unit to carry on all the processes.

Combinations of these methods are possible, for example a complete unit for the bulk of production, one or two processes being carried on in other shops.

Any general production scheme that does not take into account all the possible methods and all the items of cost and locates the heat-treatment department at a disadvantage in production routing or without consideration of its peculiar requirements will either directly or indirectly increase the cost of manufacturing. This is particularly true when heat treatment plays a large part in production. It is of importance to locate the department to good advantage for production, and it is equally important to take into account the requirements for its operation and the necessity of obtaining comfortable working conditions.

CHAPTER XV

EQUIPMENT ARRANGEMENT AND BUILDING DESIGN FOR STEEL-TREATING PLANTS

Principles Governing Arrangement of Equipment in Unit Heat-treating Plants.—When production requires high-priced machinery and highly trained labor, the arrangement of equipment may, from the standpoint of economy, be of more importance than the location of departments or buildings. Haphazard arrangement is sometimes due to unforeseen expansion. Production increases, requiring new machinery that is located in any available space, and work in process may, therefore, move to and fro from one operation to another. Because of this, operating cost is usually high, perhaps so high that competition cannot be met without loss. Market conditions over which the management has no control may also be responsible for loss, but when competitors are operating successfully, a careful analysis usually shows that such haphazard arrangement is responsible for a manufacturing cost too high for successful competition. When the equipment is arranged systematically, and modern methods of handling and transfer are introduced, a large saving in manufacturing expense usually results.

Successful methods of arranging equipment that keep manufacturing cost low are based upon definite principles behind which lie a demand for reduction of handling and transfer, for a lower expense for labor, and for less material in storage. However fixed these principles may be, the final arrangement must also be based upon a number of other factors, for example the type of production, the kind of equipment, the size and shape of the building in which the equipment is to be housed. Some of these factors—production, equipment—are fixed; others, such as the building itself, can be modified. If future construction is being planned, the building can often be fitted to the equipment this being done very frequently in modern factories.

From these principles there have been developed, particularly for the machine shop, which has naturally received the most

attention, methods of equipment layout that are almost standard. So successful have these methods been that they are often applied in other departments without giving much attention to the condition of operation. The result has usually been the opposite of that expected, production being reduced rather than increased. Methods of arrangement that work well in the machine shop may give poor results in the heat-treatment department with its radically different equipment, operating methods, and handling requirements. Some heat-treatment processes, made up of simple heating and cooling operations on parts of small size, resemble, to some degree, processes of the machine shop, so that the equipment can be arranged in a somewhat similar way. Others, as, for example, carburizing, require so much intermediate handling that a very different arrangement is necessary. The arrangement of equipment in the average heat-treatment plant can, therefore, be expected to differ from that of the conventional shop.

Classification of Methods of Arranging Equipment.—The nature of the processes and the equipment required influence the arrangement of heat-treatment equipment, but other factors, such as the kind of fuel used, the design of furnaces, the space required for handling, the transfer distances, and the size and shape of the building, must also be considered. This last factor can be eliminated if the building is designed for the equipment, as already suggested, a method that may seem like placing the cart before the horse, but one that has been responsible for marked gain in economy. On account of the varying factors, there is no "best" method of arranging equipment, although there is one that is rather generally favored. The methods employed group themselves into three general classes and the arrangement of any individual plant may follow one of these or a combination of two or of all three. These three methods will be termed "wall layout," "cross-row layout," and "center-line layout."

Wall Layout.—In wall layout, the principal furnace equipment is arranged along the walls of the building, the furnace doors facing toward the center of the room. This layout is quite extensively used, particularly with narrow rooms, to obtain a larger working space when the equipment must be placed in two rows. Furnace equipment is also frequently placed along one wall when the flow of production is across the building. For

example, in the building layout of Fig. 147 (Chap. XIV), the furnaces for heat treatment can be arranged very conveniently along the wall nearest the forge shop. Wall layout has advantages in narrow buildings and in simplifying the transfer from

FIG. 155.

one furnace to another. It has disadvantages in the furnace space lost if many doors are required through the walls, and in the crowded working space in the center of the room. A typical wall layout is shown in Fig. 155.

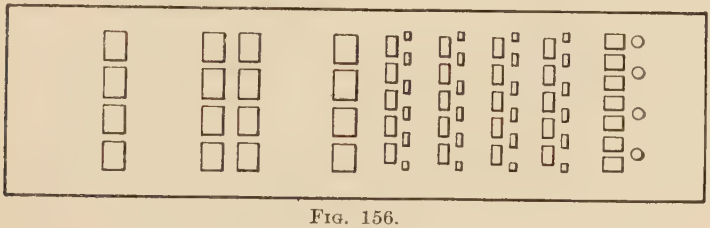


FIG. 156.

Cross-row Layout.—Cross-row layout resembles the usual arrangement of machinery and, for this reason, is often adopted. In Fig. 156 is illustrated a typical layout of this type. In Fig. 157 is shown a combination of wall and cross-row, with the flow of

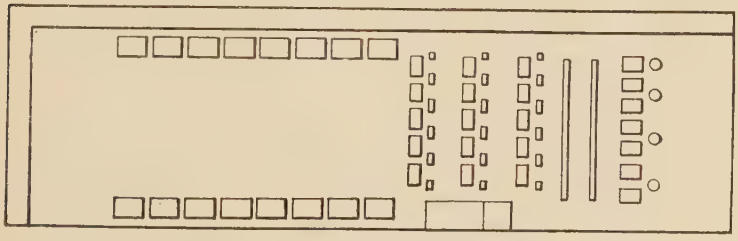


FIG. 157.

production from one end of the building to the other. Cross-row layout is well adapted to continuous furnaces and is, therefore, often combined with other types of layout to permit the introduction of such furnaces. Wall layout can also be adapted to

continuous furnaces if these are placed at some distance from the wall. The principal disadvantages of this arrangement are the inconvenience of installing the piping and the crowded working spaces.

Fig. 158.

Center-line Layout.—The third method of arrangement—center-line layout—is one that is usually preferred in the average plant because more adaptable to general operating conditions.

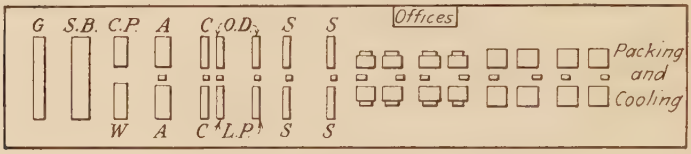


Fig. 159.

Center-line layout arranges the principal equipment along the longitudinal axis of the building, as shown in Figs. 158 to 162, inclusive. Examination of these will show that center-line

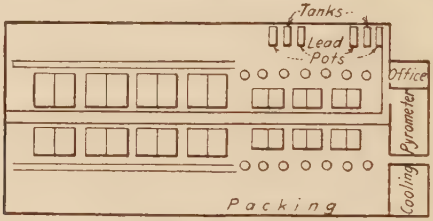
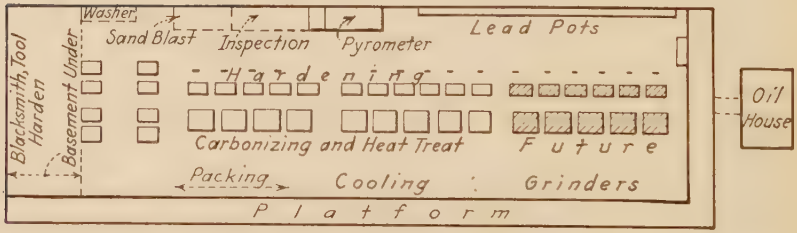


Fig. 160.



layout can be divided into two types. In one, the equipment is placed in rows on both sides of the line so that furnaces on the two sides are back to back. In the other, which might be considered as a modification of cross-row layout, the equipment is

arranged in groups, blocks, or short cross-rows along the center line. The first type is illustrated in Figs. 160 and 162; the other, in Figs. 159 and 161. In Fig. 158, a convenient combination of center line and cross-row has been made to provide for continuous furnaces.

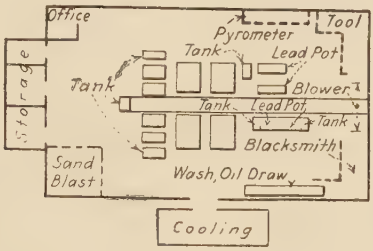


FIG. 161.

Another division may be made in methods of center-line layout, as in Fig. 163. Here the principal equipment is so separated into classes that the processes conducted on one side of the line are quite different from those conducted on the other. In Fig. 162, the furnaces are placed back to back, but the equipment is grouped according to its purpose on each side of the center line.

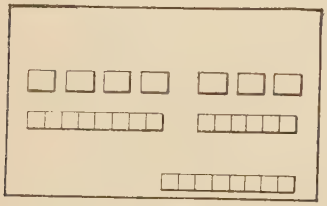


FIG. 162.

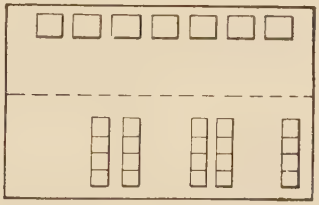


FIG. 163.

Advantages of Center-line Layout.—When conditions permit its use, the layout of Fig. 158 has many advantages over other types. By placing the principal equipment in the center, ample room is available along the walls for the remainder. More equipment can be introduced and more working space obtained than with other types of layout, as a comparison with the layout of Fig. 157 will show, this including exactly the same furnace equipment. It is evident that more equipment can be introduced in the arrangement of Fig. 158 than in that of Fig. 157, with much more working space available. As compared with wall layout,

it will be seen that door space will cut down the number of furnaces that can be placed along the wall and that the placing of other equipment in the center will interfere with the working space and cause considerable inconvenience in handling. The layout of Fig. 158 has, also, an advantage in flexibility. It is arranged to allow expansion along a definite line, but if changes in production require a change in furnace equipment, this can be arranged in any way desired in the space left for future equipment. This layout is also adapted to the usual type of building construction, without regard to size. It permits easier ventilation and better conditions for the workmen and simplifies the necessary piping. With the arrangement of Fig. 157, a change in the type of equipment would necessitate much labor in rearranging.

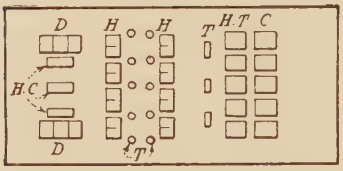


Fig. 164.

For small plants with a fixed production, the layouts of Figs. 160 and 161 are also suitable. Plenty of working room is provided, although ground space is limited. A similar arrangement for carburizing and hardening furnaces is shown in Fig. 162. A comparison with Fig. 163 will show the advantage of center-line layout in providing better working space and working conditions. If, in Fig. 162, the hardening furnaces shown along the wall had been placed in the corners, even more space would have been available.

Center-line layout has an advantage over the others in that proper ventilation is more easily obtained. Circulation of air passes from the sides to the center, and in warm weather the operators are not confined to a hot zone. It has also an advantage in flexibility, if future expansion is considered, this being particularly true of the arrangement shown in Fig. 158. Center-line arrangement has also advantages in handling and transfer, because ample working space can be provided. The distance through which loaded carburizing boxes must be carried is very short, and transfer of the parts to the hardening furnaces and then to the cleaning equipment is direct.

In Fig. 164, a complete cross-row layout for a small plant, the flow of production from one end of the building to the other

follows the usual practice of the machine shop. It has been shown that more space must be allowed for this than is needed for other methods of arrangement. If the flow of production is followed, it is evident that distances are none too short. Parts must pass in and out of the rows, thus increasing the distance between the different operations. The limited space for the temporary storage of parts in process may cause some confusion in handling. In the arrangement shown, the usual equipment, with furnaces loaded and unloaded at one end, is presumed. If the equipment consists of continuous furnaces through which the parts pass, this cross-row arrangement offers some advantages over the other methods and may be required, but more space between the rows must be provided.

Selecting the Proper Arrangement.—The selection of any method of arrangement will depend, as stated, upon the character of the production and of the equipment, but no scheme can be made complete without taking into account the effect of building design, working conditions, methods of handling and transfer, to which some reference has been made, and, also, other items such as furnace support, storage, and piping systems, items of importance not only in the arrangement of equipment but also in connection with the design of the building. Some of these items have been considered briefly, others will be covered in detail in this and other chapters. Building design, however, is closely connected with equipment layout and with operating efficiency. This, together with the other factors that affect it, must be considered before a completely satisfactory layout can be made.

Housing the Heat-treating Department. Building Design.—The housing of heat-treatment plants in buildings placed in out-of-the-way corners and constructed as cheaply as possible is a practice that is rapidly becoming practically obsolete. The "tin shed" has been replaced by well-constructed buildings designed to meet, as far as possible, the operating conditions with more attention to the human element. The improvement in building construction has been well repaid by decreased operating costs and labor turnover. The necessity for a building design that will meet the operating requirements has been recognized in other lines of industry, for example foundries and forge shops, working under similar conditions, and a general type of construction that will meet these conditions has been developed.

Following the practice for foundries, forge shops, and other industries of similar nature, buildings for general heat-treatment processes are now usually constructed with one story only. Such construction permits proper ventilation, and the cost of housing the department is usually lower than it would be if the building had more than one story. For ventilating purposes, a monitor roof is usually provided, supported either by the side walls of the building or on columns within the building. A cross-section of a building of the latter type is shown in Fig. 165. A design of this kind is well adapted to wall layout.

Monitor roofs are far from being satisfactory ventilators and are also costly. If not of sufficient height, or if the building is not placed with reference to the prevailing wind, good air circulation may not be possible at all times. If other buildings of greater height are placed near-by, the draft produced by the wind will be reduced. In a number of plants, it has been found necessary to increase the height of the monitor after the building had been placed in service. In warm, fair weather, monitors will usually be satisfactory, but in stormy weather or in the winter time, when ventilation may be needed the most, it is usually necessary to close the windows, stopping, of course, the air circulation.

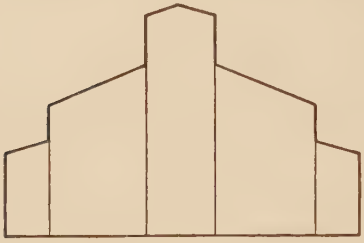


Fig. 165.

In order to avoid the unsatisfactory features of monitor construction, ventilators may be added. Better still, and usually with much less expense, the ordinary peaked roof can be used, ventilators of the revolving type being placed along and on each side of the ridge. With such construction, ventilation will be positive, and there will be no pocket to hold and recirculate waste gases. Figure 166 is a photograph of a building constructed in this way.

The method of roof support may affect furnace layout if supporting columns are required. The columns supporting the roof in Fig. 165 must be spaced at intervals and, if wall layout is used, the arrangement of the furnaces must conform to the position of the columns. If the monitor roof is supported by two rows of columns, one at each side, a center-line layout

may be hampered because the furnaces must be placed between the columns or out of line with them. The roof of the building shown in Fig. 166, however, can be supported by a single row of columns in the center, and the arrangement of furnaces will be less difficult. A clear working space without columns permits the most freedom but is usually more expensive.

FIG. 166.—Building for heat treating. Showing ventilators at peak.

Machine shops are now commonly housed in one-story buildings with low saw-toothed roofs, as sketched in Fig. 167. Departments for steel treating have been successfully housed in such buildings, but, because of the low roof, ventilators and hoods are necessary to carry off the waste gases if combustible fuel is employed, thus adding to the expense of installation. Slots in the roof similar to those located above the track in large covered railroad stations are an aid to ventilation but must be put in when the building is constructed.

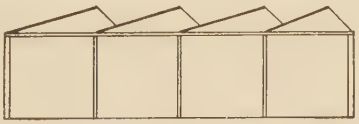


FIG. 167.

Ventilation.—In any building, particularly one intended for heat-treatment processes, working conditions and equipment arrangement may be affected as much by the design of the wall and the placing of its doors and windows as by the design of the roof and the location of its supports. Satisfactory ventilation requires not only an outlet, but also an inlet to provide for the volume of air necessary for proper circulation. Conventional wall construction, with windows placed at intervals, well above the floor, with doors some distance apart, may allow an ample volume of air to enter when all are open, but when weather

conditions make it necessary to close the openings, good circulation may be impossible. Such closed wall construction can be responsible for high room temperatures and difficult working conditions from which the furnace operators will find little relief.

To allow ample air circulation in buildings containing furnace equipment, another type of construction is now commonly used in which the lower part of the wall is made up of doors either rolling, like a window shade, or folding. When the entire wall can be opened, more than ample air circulation will be obtained, but if weather conditions require that the doors be closed, the air current will be stopped. If roll, or solid folding, doors are used, the light will also be cut off, a disadvantage that does not go with conventional wall and window construction.

All the advantages of both solid and open wall construction may be obtained by a combination of the two, placing doors at regular and comparatively short intervals in walls of conventional design. An excellent arrangement alternates two wall sections with one door. Roll doors fit in well, having one advantage in that they are never in the way, but folding or swinging doors should be used at the entrances and exits through which work in process can easily pass. For air inlets, when the doors are closed, ventilators should be placed in the wall sections. The wall spaces can be used for offices and other rooms and to provide a place for storage. Additional light, to compensate for that cut off by the doors or rooms, can be obtained by placing a row of windows around the building and above the doors.

Construction of this kind, shown in Figs. 166 and 174, is an excellent compromise between the different methods, will have little or no additional cost over any other method, and can be applied to any general scheme of equipment arrangement, although some modification may be necessary for a few types of wall layout.

Furnace Support.—Building construction, in so far as roof and wall design is concerned, lies outside the field of heat treatment, at least in its details. The expense of construction, however, is an indirect charge against the cost of operation, and the method used may affect the direct operating cost, and a brief discussion of these factors is, therefore, necessary. The design of floors, on the other hand, including furnace support, the arrangement of piping systems, and other details, is closely connected with

equipment arrangement and operating methods and will, therefore, be given more attention.

Furnaces of heavy construction require a support much stronger than can be obtained with the ordinary floor so that individual foundations are usually provided. This method provides for a support of sufficient strength but has some serious disadvantages among which are the cost of construction and the loss of flexibility in the arrangement of furnace equipment. The cost of furnace support is decreased and greater flexibility for arranging equipment is obtained by providing, in place of individual foundations, a concrete slab in floor areas assigned to furnace equipment. In Figs. 158, 160, and 161, for example, a concrete slab placed on each side of the center line would provide ample support for all furnaces and allow any arrangement or rearrangement desired.

The method used for furnace support may, to some degree, be dependent upon the arrangement made for storage space. If a limited ground area requires that a basement be provided under the entire building, individual foundations for the furnaces will usually be required, or else some form of pier support. Such a basement provides a good location not only for stores, but also for operating equipment such as pumps, blowers, tanks, and coolers. The expense of such construction is high, however, and if the building is large, the storage space may be much greater than necessary. A basement placed under a portion of the floor may give all the storage room needed and the heavy furnace equipment can then be supported on slabs. In Fig. 158 is shown a convenient location for a basement under part of the building. Basement storage has many advantages, but when ground room is available, an additional building in close proximity is usually provided, or, if the building is large and has space for the purpose, a room may be partitioned off to provide for storage, methods that are more common on account of the lower cost.

Piping and Trench Systems.—In all heat-treatment plants using oil or gas fuel, provision must be made to supply fuel to the furnaces. Nearly all plants require quenching mediums, which must be delivered to the quenching tanks. The piping required for fuel, air, and quenching oil and water can be arranged in so many different ways that the advantages of a definite system, planned together with the equipment arrangement,

are often overlooked. In some shops, all pipes are carried overhead; in others, only air lines; in still others, underground or in trenches. In more recent shops, all lines are carried below floor level. If a full basement has been provided, pipe lines are easily carried on its ceiling, feeding through the floor to the

Fig. 168.—Trench system.

different points served, but if there is no basement, trenches can be employed.

It is evident that the cost and ease of installing piping systems will depend, to some degree, upon the type of layout. In wall layout, for example, the piping must be carried to both sides of

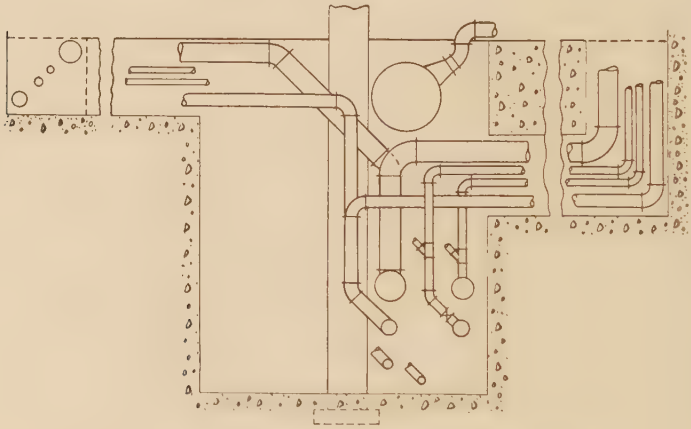


Fig. 169.—Main trench with side trenches—cross section.

the room, requiring double lines. In a cross-row layout, the main pipe lines can extend through the center of the building, but a branch line will be required for each row. Center-line layouts, on the other hand, especial y the type in which furnaces are placed back to back, require only a single main line for each material piped, with short branches. In Figs. 158, 160, and 161,

the principal furnace equipment has been placed on each side of a central trench through which feeder lines pass. The equipment of Fig. 159 could also be supplied in the same way if placed a little farther away from the center line.

The plan of Fig. 158 includes a basement in which blowers, quenching oil pumps, and water pumps, if needed, can be placed, and from which the lines can pass into the central trench. A complete plan for a trench system in accordance with this arrangement is shown in Fig. 168. On either side of the central trench and located on the line of the quenching tanks are smaller parallel trenches for the quenching oil and water-inlet and outlet lines. Between the two lines of trenches are cross-trenches placed at regular intervals, through which the inlet and outlet lines to and from the tank system are connected with the main lines in the center trench.

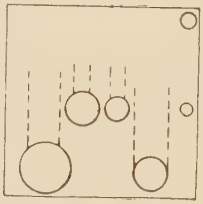


FIG. 170.—Side trench. Cross section.

If the center trench is made wide and high enough, all pipe lines can be easily installed and are accessible for repair. Figure 169

FIG. 171.—Center line layout—trench cover.

shows a cross-section of the trenches of Fig. 168, including the large central trench in which the pipe lines are carried on one side, the other being left open for passage. In this sketch, a central supporting column is shown. The supply trenches at each side are shown, with the piping arrangement, and two methods of locating the cross-trenches are indicated, one well

below, the other just below floor level. The large center trench should be at least 8 ft. high and 6 ft. wide; the smaller supply trenches, about 2 ft. square in cross-section. This method of

Fig. 172.—Construction of main trench and side branches.

placing piping systems is suitable for large plants, for example that shown in Fig. 158. A plant of this size will require a large

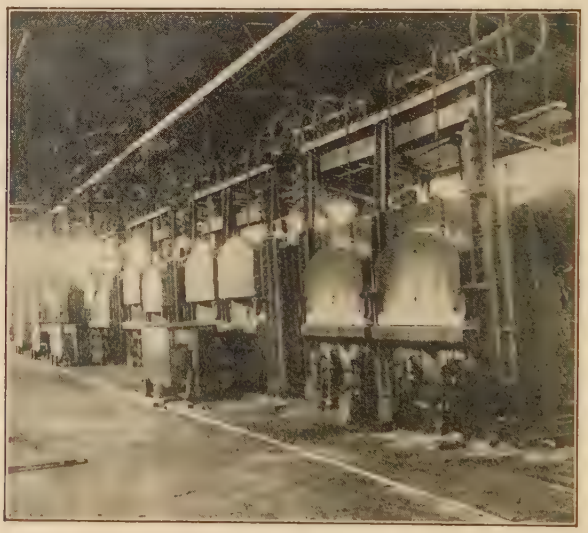


Fig. 173.—Center line layout with car tanks and track.

pumping system if fuel oil is used, and the building containing pumping equipment can be placed, as shown in the sketch, so that the pipe lines pass directly into the central trench. In

small plants, a central trench of the size indicated will not usually be needed, a cross-section 2 ft. square or 3 by 2 ft. being ample for all the piping. The trench systems shown in Fig. 160 and 161, plants of small size, follow the general design shown in Fig. 168, but have trenches of smaller size. The piping can be arranged as shown in Fig. 170.

The location of pipe lines in trenches improves the appearance of the room and, also, simplifies installation and repair. If space for the trenches is provided when the floor is built, no great expense is involved. For accessibility, manhole covers can be provided at the floor level, the upper surface corrugated for

FIG. 174.—Center line layout with stationary quenching tanks.

safety. The convenience of this arrangement can be seen in the photograph, Fig. 171. The method of construction is shown in Fig. 172. Figures 173 and 174 show the fronts of the furnaces.

In selecting any general arrangement for the furnace equipment of a heat-treatment plant, transfer and handling, building design, storage, piping systems, as well as the type of production, must be taken into account. The degree to which they will affect the arrangement depends upon the individual conditions, and each installation must, therefore, be considered by itself. The general principles that have been discussed in this chapter can be applied to almost any installation, whether it be large or small, to determine the arrangement most suitable for the purpose required.

CHAPTER XVI

LABOR, SUPERVISION, AND COST

Management in Steel Treating.—Steel treating has its own peculiar requirements for labor, supervision, and cost accounting, but how these are managed will depend upon the importance of the processes in the scheme of production. If steel treating plays only a small part in the total production processes, the methods of meeting the requirements will usually be based upon those employed for the entire production. On the other hand, steel treating may play a large part, and these peculiarities will, therefore, be recognized. The labor requirements of steel treating and methods of compensation differ from those of other departments, although modern labor-saving equipment is bringing the two nearer together. Other departments require a supervision of production that may or may not be partly technical. Steel treating requires technical as well as production supervision, and between the two, a line is not always easily drawn. The items of cost in steel treating are not those of other departments and cost accounting must sometimes take this into account. The principal requirements for labor will be briefly discussed from the standpoint of the steel-treating department rather than from that of management and cost accounting.

Passing of the Skilled Operator in Mass Production.—Modern mass production places little dependence upon the all-around skilled operator and his ability to plan and to adapt his tools to any and all requirements. The operator now usually performs but one, or perhaps two, operations closely connected; and is provided with proper equipment and instructed in the method of procedure, all in accordance with a definite plan. Skilled supervision and planning have taken the place of skilled labor. Exceptions occur, but rather in connection with a small and varied production than with mass production. Steel treating, once an art dependent upon the knowledge and skill of the

operator, now rarely requires more than obedience to definite instructions. Furthermore, the introduction of labor-saving equipment requires more mechanical skill and less metallurgical skill on the part of the operator.

A planned production may often replace the individual operator by a gang or crew. Tasks that were all performed by a single operator, perhaps with the aid of a helper, are divided among the crew, each member having a single operation. Loading and unloading a battery of large batch furnaces will usually be accomplished in a much shorter time by a trained crew than by individual operators. On the other hand, mechanical equipment may do away with any necessity for even semiskilled labor.

The skilled hardener is now a supervisor rather than an operator. Here and there, the all-around skilled artisan is in demand, but this demand is insufficient to insure the supply. His departure is sometimes felt severely. Mass production is not easily applied to an intermittent and varied output, of which tool hardening is an example, and here personal skill is an asset. Training in mass production does not make an all-around skilled hardener, however. An operator trained in production methods usually makes a poor tool hardener as many have found by trial. Special training is required—a training that should bring with it the ability to meet emergencies.

Training for Special Production.—The passing of the skilled hardener is regrettable, but should not be a serious difficulty, because his methods are no longer secret but follow definite principles that should now be thoroughly understood. Some of the methods of special practice have been discussed in previous chapters. In such methods, the special operator should be trained according to a plan just as definite as that of a standardized production. Those who are familiar with the methods of a large production do not always understand that other methods are required for special hardening. The same type of planning and supervision, however, can well be applied to both.

Responsibility for Planning and Supervision.—The responsibility for the planning and supervision of steel treating may be divided, because of the radically different fields that supervision must cover. Responsibility for quality, for ensuring that the physical specifications are met, requires a training different

from that necessary for producing the quantity required. Hence, the metallurgical department may be responsible for inspection and for technical information and instructions, actual production being left to the production department. Inspection and technical methods should always be under the control of the metallurgical department. Planning and supervision, however, are so closely tied with quality that the field of the metallurgical department is extending into that of production with responsibility for equipment and operations.

Planning requires the selection of furnaces, and, perhaps, their design and construction, and also the selection of other equipment required. The labor requirements will depend upon the type of equipment as well as upon the operation to be performed. Labor should be considered in connection with equipment, therefore, and comparison made on a basis of cost. Continuous production and intermittent production require different planning; and equipment and methods should be selected on a basis of the conditions to be met. Methods suitable to one set of conditions may be very undesirable under another, and exact copying of the methods of others is rare. Familiarity with such methods, however, over as wide as possible range of practice is a valuable guide. Planning is a continuous process. Methods are not set permanently but are subject to constant change as improvement becomes possible.

Supervision in Steel Treating.—Supervision of steel treating, like planning, has a divided responsibility, but direct supervision of production and labor is usually given to the production department; technical supervision, to the metallurgical department. Direct supervision is usually given to a foreman who, particularly in small shops, may be responsible for both technical and production supervision. In large shops, responsibility is usually divided among assistant foreman each of whom has charge of some branch of steel treating. Metallurgical supervision is concerned principally with the temperatures employed and perhaps also with the time required. In modern shops, recorders or automatic controlling devices make continued supervision unnecessary. Such devices are usually observed and kept in action by a "pyrometer man," or in small shops will be observed by the foreman and repaired outside. Technical supervision may also include inspection, particularly process inspection as described in a previous chapter.

Technical Supervision in Other Departments.—Technical supervision may extend, at least occasionally, to other departments, because heat treatment may affect, or be affected by, the results of the processes carried on in those departments. Machinability often depends upon heat treatment although the condition of the cutting tool is sometimes more important, a fact that must be thoroughly understood by the technical supervisor as well as by the shop man so that responsibility for trouble can be properly placed. Supervision to prevent the checking or cracking of hardened surfaces should also be extended to the grinding room. The layman does not always distinguish between cracks due to hardening and cracks due to improper grinding although there is a distinct difference. Sometimes a change in the method of hardening may improve conditions in grinding, but dry grinding, too slow rotation of the piece being ground, too high speed of the grinding wheel or a wrong grade, and particularly crowding can be responsible for surface cracks or even complete fracture for which the blame is sometimes wrongfully placed upon the steel treating department, an error that technical supervision can avoid.

Compensation of Labor.—Planning must take into account the method by which the operator is to be compensated and must decide whether or not a wage incentive is to be added. The three general methods of payment are respectively a straight hourly rate, piece-work rate, and a supplementary bonus. All of these have been applied in steel treating, but adding a wage incentive may be somewhat a problem because there is usually so little leeway for the development of personal skill by which production can be increased. Here and there an incentive may be worth while to encourage the maintenance of a planned production. No plan, however, should attempt to go beyond the capacity of the operator, and an incentive is therefore inadvisable if aimed in that direction. Of the two general forms of incentive, piece-work and a bonus, piece-work is less easily applied to steel treating controlled as it is by time and temperature. Piece-work rates offer a temptation to hurry up the output at the expense of quality. Most operators know, or soon learn, that a higher temperature speeds up production and that the fire-ends of pyrometers can be so placed that the increase in temperature is not indicated.

Piece-work, on the other hand, is successfully used in steel treating practice and simplifies cost accounting. But control of production is necessary. If inspection is complete and shows up defective work, such work can be turned back to the operator to be retreated without pay. However inspection will not always indicate defects in treating. Production may be limited and carefully controlled, but such control limits the incentive offered by a piece-work rate. A regulated piece-work rate differs little from a straight hourly rate particularly if some form of bonus is attached or a definite production is required. Much of the argument for and against piece-work rates overlooks the fact that differences in methods are usually differences in name only.

The payment of a bonus for maintaining a definite production is probably the most satisfactory labor incentive if an incentive is required. Such a bonus may be disguised under the form of a piece-work rate or a daily rate for a definite production. On the other hand, a bonus paid to the individual may be nothing more than a disguised piece-work rate, although such a bonus often covers more ground. The gang bonus or a bonus spread over a department, perhaps including the sub-foreman and straw bosses, who are usually responsible for the production obtained, offers none of the disadvantages of piece-work and often results in reducing the number of men required. A bonus may be paid for other purposes; for example, an attendance bonus for full time during a pay period. These indirect incentives have their field, but, as a rule, the payment of a suitable hourly rate is quite satisfactory. A beginner may be paid a rate below the standard, this being reached as soon as his experience so justifies.

Working Conditions.—The price of labor frequently depends upon the working conditions in the shop. The employer who has provided proper conditions will have his choice of the market at the current rate or may perhaps find that he can pay slightly less. Proper ventilation, already discussed, is an asset. In modern shops, men are now rarely required to endure high temperatures. Occasionally this is necessary, but if so, the time should be comparatively short. Large fans, the so-called "man-fans," often make it possible for men to work comfortably in close contact with hot furnaces. Occasional rest periods for men carrying on heavy duties should be allowed. Shower baths are an asset in many steel-treating shops, and in some are essential. Working conditions vary so much that rules cannot

be laid down, but in modern practice attention to proper working conditions has paid good dividends.

Cost in Steel Treating.—More attention has been paid in the literature to the technicalities of steel treating than to the operations of steel-treating shops, and the subject of cost has been particularly neglected. Quality is essential in any product, but cost is vital if production is to continue. Items that affect cost, material, equipment, methods, have been discussed in previous chapters, but here methods of determining cost will be considered more from the standpoint of steel treating than from that of cost accounting. Cost is too often observed from one angle and invisible items are easily missed. Changes made to save labor are sometimes costly because of an increased fuel consumption. Equipment that will give longer service may be costly because of the increased capital investment required. Cost accounting can be made an expensive process if too much detail is included.

Object of and Items Entering into Cost Accounting.—Cost accounting has two objects, namely, to determine the actual cost of production and to obtain data by which cost may be predicted. The principal items of cost are:

Material
Labor
Expense (Burden or Overhead)

Material is divided into direct and indirect, direct entering the finished product. Indirect material is required in manufacturing but does not enter into the finished product. Steel to be treated is direct material, but carburizer, for example, is indirect material. Labor is likewise divided into direct and indirect, the one being applied to the product directly, as in loading and unloading furnaces, the other to non-productive operations, for example, moving direct material from one process to another. Expense —burden or overhead—is largely made up of the cost of indirect material and labor and other expenses such as rent, light, heat, power, supervision, and administrative and selling expense that cannot be immediately charged to each individual item produced.

Distributing Overhead.—Cost is sometimes determined for complete assemblies or for the total production, but accurate accounting must usually determine the cost of making each individual piece. The direct labor and material required for

each piece can usually be determined with fair accuracy and without much difficulty, but the proper distribution of the overhead expense is the principal problem in cost accounting. Overhead may be distributed as a percentage of the direct material or of the direct labor, or of both combined; distribution as a percentage of the direct labor being the method most favored. All indirect expense may be summed up and distributed, but the operating expense of each department is usually determined and the general expense prorated to the individual departments. Expense is usually determined for a particular period, for example, one year or one month. A typical example of distribution of expense to a steel-treating department for a yearly period follows.

Direct Labor	$10,000
Overhead:	
Indirect Labor	$ 2,000
Expense on Building	500
Heat, Light, and Power	2,000
Insurance and Taxes	300
Depreciation	900
Repairs	700
General Expense	1,000
Direct Supplies	1,500
Indirect Supplies	600
Fuel	7,000
Water	1,100
Miscellaneous Expense	400
Total	$18,000

Overhead on Direct Labor 180 per cent.

Individual cost can be determined very accurately if the production is simple, consisting perhaps of one item, or of a few items, of similar character. If, for example, the output in the year was 140,000 shafts of the same kind, the cost of treating each would be $0.20. If three shafts of different sizes were treated, the direct labor would perhaps be distributed as $5,000 for one kind and $3,000 and $2,000, respectively. The overhead being 180 per cent, respective totals are $14,000, $8,400, and $5,600. Assuming a production of 40,000, 50,000, and 60,000 of each kind, individual cost would be, respectively, 35, 16.8, and 9⅓ cts.

Advantages and Disadvantages of Furnace Rate.—This method of determining cost is satisfactory enough for a simple

production, such as that considered, but accurate determination is rarely possible if a large number of pieces is treated, especially if a number of different processes are required, and only if many more details are included. For a complex production that depends more upon the equipment than upon direct labor, cost can be determined more accurately for each item if based upon the expense of operating the equipment, upon the expense of operating the machine tool or the furnace, for example, the so-called machine rate. The principal objection to the method is the time and the work required to set the rate. When once established, however, an accurate determination of individual cost is comparatively simple, and changes in the rate that become necessary are easily made.

The method of establishing a furnace rate can be illustrated by simple examples. Using the same data, given in the last example, assume ten furnaces of the same size operating continuously. Total charge for direct labor is \$10,000 or \$1,000 for each. Overhead, total \$18,000, is \$1,800 for each. Assuming 8 hr. operation daily for 250 days, total operating time is 2,000 hours. The hourly rate is;

Labor	\$0.50
Overhead	0.90
Total	\$1.40

In general production, however, there is a certain amount of idle time for which allowance should be made. Presume the records show a total time in productive operation of 1,400 hours. Total expense is \$28,000 or \$2 an hour. Added expense for idle time is approximately 43 per cent. The account then stands

Operation	\$1.40
Idle time, 43 per cent	0.60
Hourly rate	\$2.00

Individual cost can then be determined by the output per hour.

This simple method is applicable to one or perhaps two process that use the same equipment, provided that this equipment is uniform. But furnaces may be of different sizes and used for several different process, and different rates will be required. Furthermore, in applying this method, a definite distinction must be made between continuous and intermittent

production. Even with a single product, production may be at its peak in one period and very small in another. Unlike the machine tool, the furnace does not stand ready for operation at all times but must be heated before production begins. The time and the fuel required are non-productive. If the breaks in production come at regular periods, for example at week ends, adding a factor for idle time and heating up is comparatively easy. Allowance for idle time for repairs can also be made. But irregular production complicates the calculation of the factor for idle time and for heating up. In general, the idle time for a long period, perhaps a year, may be determined and spread over that period or may be spread over the next productive period. This is usually cared for by the addition of a supplementary rate based upon the idle time and the extra expense of heating up. This supplementary rate must usually be combined with the machine or furnace rate to determine cost accurately.

Factors of Idle Time and Heating Up.—Idle time and the cost of heating up must be taken into account in predetermining cost, particularly in comparing different methods and equipment. Large and expensive equipment may be economical for continuous production, but expensive if production is intermittent because of the high rate that must be charged and the expense of heating up. For an intermittent production, the older batch furnace may prove more economical than the modern, large, continuous furnace, particularly if the former is heated by oil and the latter by electricity. Small, continuous furnaces may be preferable to large. Neglect of these factors has often been responsible for a large increase in cost when new, and presumably economical, equipment has been installed.

Adjusting Furnace Rate to Different Processes.—A further allowance must be made in applying the furnace rate if more than one process is carried on in one furnace. Very obviously, the hourly rate for carburizing will differ from that of tempering, and if both operations are conducted in the same furnace, different rates must be supplied. This, of course, requires more detailed information than that given in the previous example. The labor required, the fuel comsumption, the direct and indirect material, and other items will differ Labor may be easily determined. The fuel consumption in each process can be determined by metering for a given period and then may be prorated as a percentage of the total comsumption. Only

occasional checking will be necessary. Other expense can be prorated or, if possible, directly applied as, for example, the cost of carburizer, which can be added to the furnace rate for carburizing if desired.

Presuming the details to be established, for which the previous simple examples will serve to indicate the method, the establishing of furnace rates for different processes may be illustrated by a simple diagram representing an average steel-treating room.

Furnaces A Furnaces C
Furnaces B Furnaces D

	Per Hour		Per Hour
Furnace A:		Furnace B:	
Carburizing	$3.00	Hardening	$1.50
Heat treating:		Annealing	$1.00
Quench	$2.50		
Draw	$1.00		
Annealing	$2.00	Furnace C:	
Normalizing	$2.75	Continuous hardening and drawing	$4.00
Furnace D:			
Lead Pots:			
Hardening	$2.25		

To these, supplementary rates should be added.

Department Cost Finding.—The machine or furnace rate has disadvantages, some of which have been discussed, but is probably the most accurate method of determining operating cost. Even if some other method of accounting is applied throughout the factory, the steel-treating department can often use the furnace rate to advantage for comparing or predetermining cost if the details of expense are available. No one method, however, is applicable to all conditions, and a study of the general methods of cost accounting will be well worth while to the steel treater. The data presented by the accounting department may be determined more from the standpoint of general cost than from that of exact, individual cost in the steel-treating department and may, therefore, be inaccurate as a standard of comparison.

Other items of expense that enter overhead can usually be estimated with accuracy, but depreciation is not easily determined in advance. Not wear and tear, which can be charged in the repair account, but obsolesence makes depreciation difficult to determine. A furnace, for example, may be kept in perfect

repair but may, and usually does, become obsolete in a few years and must be replaced. Even if the type of furnace does not become obsolete, changes in production or in method may require entirely new equipment. Experience is the best guide to predetermining depreciation, and past practice indicates an average life of equipment of about seven years. A fair allowance for depreciation is therefore 15 per cent annually. Experience may dictate a longer or a shorter period for individual production, but the figure given represents a general average.

Capital Investment Entering Cost.—An important item that does not always appear in cost figures is the capital investment. Interest on capital should always be included in expense, particularly if a comparison of equipment is to be made. In accounting, the investment is usually represented by fixed or permanent assets, for example, land and buildings, tools and furnaces. Material used up in process is not so included but is placed in an expense account being paid for by the purchaser. But capital is required for such material and sometimes material for process is not easily distinguished from a capital asset. For example, equipment that is rapidly used up and therefore charged to expense may be replaced by equipment that lasts a long time but at a higher price. Perhaps the short-lived equipment cost $30,000 and the longer-lived, $300,000. This item approaches a capital investment. If the second type lasts ten times as long as the first, the cost is not the same but higher because of the difference in the capital invested and the interest thereupon. Neglect of such invisible items may be responsible for increased cost.

Quality and Cost.—Items of cost, particularly those that are not self-evident, may be overlooked because the first requirement is that of service. Quality is of such importance that preference is often given to a higher-priced product, even if the quality of the lower-priced is identical, or perhaps slightly better, if there is no exact basis of comparison. Modern control of steel treating entered industry because of a demand for quality. The metallurgist was, and still is, frequently looked upon as a scientist, his function being to obtain quality with cost a secondary point. "What does a metallurgist know about cost?" has been a common question. By experience, however, a more exact knowledge of the requirements of service has been obtained, and cost has, therefore, increased in importance and rapidly. In seeking quality, the steel-treating department must usually aim

at producing a product that will give the required service at the least cost.

Quality does not always mean high-priced material and elaborate treatment. Sometimes simple methods of long standing are replaced by supposedly more scientific methods only to result in failure in service because of unforeseen conditions. Often, the replacement results in no improvement in service although the cost is increased. Quality is not necessarily impaired by low-priced material, or by material slightly outside of the usual specifications, nor is it necessarily impaired by simple manufacturing methods. Material and methods, however, frequently offer convenient alibis for failure due to unknown causes, and, as a result, others are introduced at greater cost, sometimes without any better results. These points have been discussed in other chapters and are important in reducing cost.

The steel-treating department is not only responsible for maintaining quality at the lowest cost and for selecting materials and methods accordingly, but also for a minimum cost of operation in using the methods selected. Such operation requires a knowledge of the details of expense, including invisible items such as capital investment, inventory of stock on hand, and the effect of idle time and intermittent operation—points that have been briefly discussed here. Steel treating is a business and differs from other branches of industry only in detail. Competition once required that first attention be given to quality, but experience has now formulated the rules. Attention has shifted to cost, which, therefore, should be known in detail whether steel treating is of primary or of secondary importance in the scheme of production. Perfect service at the lowest cost is the rule that guides.

APPENDIX

HEAT-TREATMENT DEFINITIONS

(*Report of a joint committee, composed of representatives of the Society of Automotive Engineers, the American Society for Testing Materials and the American Society for Steel Treating.*)

During recent years, certain confusion has arisen in regard to the meaning of commonly used heat-treating terms. For instance, in one locality or trade, any operation of heating and cooling resulting in a softening of the material is being called "annealing," whereas in other places to "anneal" means not primarily "to soften" but to heat to above the critical temperature and cool very slowly. Similar confusion as to meaning and application exists in regard to other terms, and as a result "annealing," "tempering," "normalizing," and the like are being used by different people to mean widely different things.

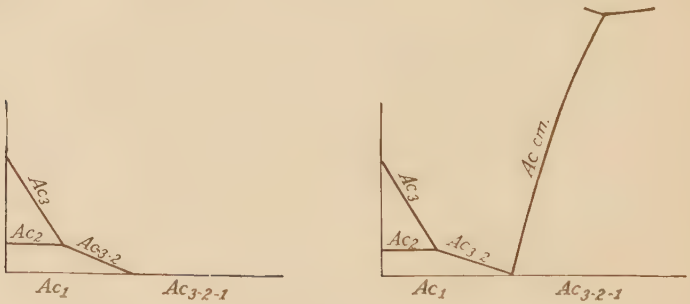


FIG. 1.—Diagram for heat-treatment definitions. (*After Howe.*)

In any attempt to define accurately the terms commonly used in connection with heat treatment, the first question to decide and the most important one is; Do the terms relate to the heat-treatment operation itself or to the results obtained by the treatment? In other words, is the term indicative of the structure or the condition obtained or the operation performed?

After careful consideration, it appears most logical and most in keeping with present day usage to have the terms so defined that they shall mean definite operations and shall not be considered as referring to the resultant structures or general conditions.

By "critical-temperature range," as used in the Definitions, is meant that temperature range illustrated by the diagram reproduced at the left of Fig. 1, which is taken from Howe.

HEAT-TREATMENT DEFINITIONS

Heat-treatment.—An operation or combination of operations involving the heating and cooling of a metal or an alloy in the solid state.

NOTE.—This is for the purpose of obtaining certain desirable conditions or properties. Heating and cooling for the sole purpose of mechanical working are excluded from the meaning of this definition.

Quenching.—Immersing to cool.

NOTE.—Immersions may be in liquids, gases, or solids.

Hardening.—Heating and quenching certain iron-base alloys from a temperature either within or above the critical-temperature range.

Annealing.—A reheating and cooling operation of a material in the solid state.

NOTE 1.—Annealing usually implies a relatively slow cooling.

NOTE 2.—Annealing is a comprehensive term. The purpose of such a heat treatment may be

a. To remove stresses.

b. To induce softness.

c. To alter ductility, toughness, electrical, magnetic, or other physical properties.

d. To refine the crystalline structure.

e. To remove gases.

In annealing, the temperature of the operation and the rate of cooling depend upon the material being heat treated and the purpose of the treatment.

Specific heat treatments coming under the comprehensive term "annealing" are

Normalizing.—Heating iron-base alloys above the critical-temperature range followed by cooling to below that range in still air at ordinary temperature.

NOTE.—In the case of hypereutectoid steel, it is often desirable to heat above the Ac_{cm} line, as shown in the diagram at the right of Fig. 1.

Spheroidizing.—Prolonged heating of iron-base alloys at a temperature in the neighborhood of, but generally slightly below, the critical-temperature range, usually followed by relatively slow cooling.

NOTE 1.—In the case of small objects of high-carbon steels, the spheroidizing result is achieved more rapidly by prolonged heating to temperatures alternately within and slightly below the critical-temperature range.

NOTE 2.—The object of this heat treatment is to produce a globular condition of the carbide.

Tempering (also termed **Drawing**).—Reheating, after hardening, to some temperature below the critical-temperature range followed by any rate of cooling.

NOTE 1.—Although the terms "tempering" and "drawing" are practically synonymous as used in commercial practice, the term "tempering" is preferred.

NOTE 2.—Tempering meaning the operation of hardening followed by reheating is a usage which is illogical and confusing in the present state of the art of heat treating and should be discouraged.

Malleablizing.—Malleablizing is a type of annealing operation with slow cooling whereby combined carbon in white cast iron is transformed to temper carbon, and, in some cases, the carbon is entirely removed from the iron.

NOTE.—Temper carbon is free carbon in the form of rounded nodules made up of an aggregate of minute crystals.

Graphitizing.—Graphitizing is a type of annealing of cast iron whereby some or all of the combined carbon is transformed to free or uncombined carbon.

Carburizing (**Cementation**).—Adding carbon to iron-base alloys by heating the metal below its melting-point in contact with carbonaceous material.

NOTE.—The term "carbonizing" used in this sense is undesirable, and its use should be discouraged.

Case Hardening.—Carburizing and subsequently hardening by suitable heat treatment all or part of the surface portions of a piece of iron-base alloy.

Case.—That portion of a carburized iron-base alloy article in which the carbon content has been substantially increased.

Core.—That portion of a carburized iron-base alloy article in which the carbon content has not been substantially increased.

Cyaniding.—Surface hardening of an iron-base alloy article or portion of it by heating at a suitable temperature in contact with a cyanide salt, followed by quenching.

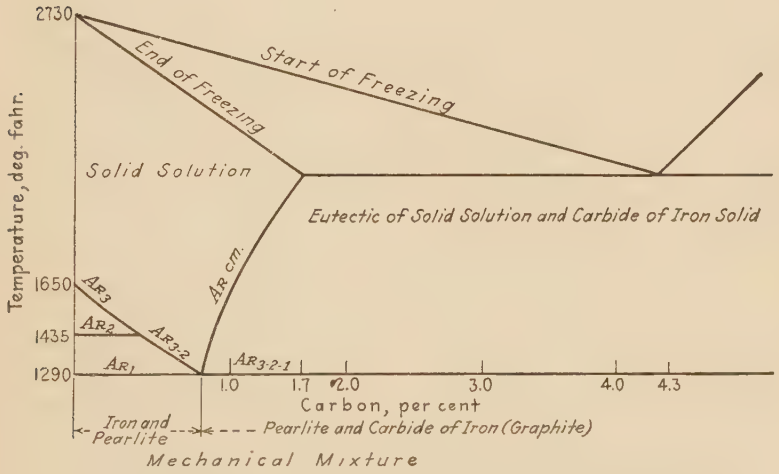


FIG. 2.—Critical temperature diagram of iron-carbon alloys: iron-carbide of iron curve based on cooling curves.

Conversion Tables of Fahrenheit and Centigrade Scales

C.	F.	C.	F.	C.	F.	C.	F.	C.	F.	C.	F.	C.	F.
0	32	230	446	460	860	690	1274	920	1688	1150	2102	1380	2516
5	41	235	455	465	869	695	1283	925	1697	1155	2111	1385	2525
10	50	240	464	470	878	700	1292	930	1706	1160	2120	1390	2534
15	59	245	473	475	887	705	1301	935	1715	1165	2129	1395	2543
20	68	250	482	480	896	710	1310	940	1724	1170	2138	1400	2552
25	77	255	491	485	905	715	1319	945	1733	1175	2147	1405	2561
30	86	260	500	490	914	720	1328	950	1742	1180	2156	1410	2570
35	95	265	509	495	923	725	1337	955	1751	1185	2165	1415	2579
40	104	270	518	500	932	730	1346	960	1760	1190	2174	1420	2588
45	113	275	527	505	941	735	1355	965	1769	1195	2183	1425	2597
50	122	280	536	510	950	740	1364	970	1778	1200	2192	1430	2606
55	131	285	545	515	959	745	1373	975	1787	1205	2201	1435	2615
60	140	290	554	520	968	750	1382	980	1796	1210	2210	1440	2624
65	149	295	563	525	977	755	1391	985	1805	1215	2219	1445	2633
70	158	300	572	530	986	760	1400	990	1814	1220	2228	1450	2642
75	167	305	581	535	995	765	1409	995	1823	1225	2237	1455	2651
80	176	310	590	540	1004	770	1418	1000	1832	1230	2246	1460	2660
85	185	315	599	545	1013	775	1427	1005	1841	1235	2255	1465	2669
90	194	320	608	550	1022	780	1436	1010	1850	1240	2264	1470	2678
95	203	325	617	555	1031	785	1445	1015	1859	1245	2273	1475	2687
100	212	330	626	560	1040	790	1454	1020	1868	1250	2282	1480	2696
105	221	335	635	565	1049	795	1463	1025	1877	1255	2291	1485	2705
110	230	340	644	570	1058	800	1472	1030	1886	1260	2300	1490	2714
115	239	345	653	575	1067	805	1481	1035	1895	1265	2309	1495	2723
120	248	350	662	580	1076	810	1490	1040	1904	1270	2318	1500	2732
125	257	355	671	585	1085	815	1499	1045	1913	1275	2327	1505	2741
130	266	360	680	590	1094	820	1508	1050	1922	1280	2336	1510	2750
135	275	365	689	595	1103	825	1517	1055	1931	1285	2345	1515	2759
140	284	370	698	600	1112	830	1526	1060	1940	1290	2354	1520	1768
145	293	375	707	605	1121	835	1535	1065	1949	1295	2363	1525	2777
150	302	380	716	610	1130	840	1544	1070	1958	1300	2372	1530	2786
155	311	385	725	615	1139	845	1553	1075	1967	1305	2381	1535	2795
160	320	390	734	620	1148	850	1562	1080	1976	1310	2390	1540	2804
165	329	395	743	625	1157	855	1571	1085	1985	1315	2399	1545	2813
170	338	400	752	630	1166	860	1580	1090	1994	1320	2408	1550	2822
175	347	405	761	635	1175	865	1589	1095	2003	1325	2417	1555	2831
180	356	410	770	640	1184	870	1598	1100	2012	1330	2426	1560	2840
185	365	415	779	645	1193	875	1607	1105	2021	1335	2435	1565	2849
190	374	420	788	650	1202	880	1616	1110	2030	1340	2444	1570	2858
195	383	425	797	655	1211	885	1625	1115	2039	1345	2453	1575	2867
200	392	430	806	660	1220	890	1634	1120	2048	1350	2462	1580	2876
205	401	435	815	665	1229	895	1643	1125	2057	1355	2471	1585	2885
210	410	440	824	670	1238	900	1652	1130	2066	1360	2480	1590	2894
215	419	445	833	675	1247	905	1661	1135	2075	1365	2489	1595	2903
220	428	450	842	680	1256	910	1670	1140	2084	1370	2498	1600	2912
225	437	455	851	685	1265	915	1679	1145	2093	1375	2507		

Degrees Centigrade $\times$ 1.8 + 32 = degrees Fahrenheit

$$\frac{\text{Degrees Fahrenheit} - 32}{1.8} = \text{degrees centigrade}$$

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